SYSTEMS MODELS FOR PROMOTING REGIONAL RESILIENCE TOWARDS REPEATED HURRICANE EVENTS

by
Khatoon Melick

A dissertation submitted to Johns Hopkins University in conformity with the requirements for the degree of Doctor of Philosophy

Baltimore, Maryland

October, 2016

Abstract

We have developed a systems approach to describe infrastructure-building scenarios in flood-prone coastal communities. These scenarios are complex because of the interaction between individual homeowner and community-level activities, and because of the need to consider short- and long-term effects. We incorporate several systems methods to enable us to examine these processes: The Unified Modeling Language (UML) is used to develop a conceptual model that includes the principle actors of the system, including homeowners, the community government and a not-for-profit insurer, and the sequences of events associated with community resilience. An agent-based model (ABM) is developed to simulate the scenarios of the conceptual model, and to clarify how the system works by quantifying the processes of the conceptual model. The mathematical relationships that describe the emergent economic behavior of the agents were explained with level plots. System dynamics (SD) and linear systems theory from sociology are used to investigate the interactions between individual and community-level behaviors. This combination of approaches helps us better understand the individual homeowner decisions that lead to the best possible outcome for community resilience.

We have also developed a probabilistic surge response model for rapid assessment of hurricane wave and surge risks in the mid-Atlantic region. This model uses the maximum likelihood principle to predict flood elevations of future potential hurricanes. For the training and verification data sets, we used 1,380 simulated surge heights generated by the US Army Corps of Engineers. Our model computes flood elevation predictions in much less time than the high-fidelity models, with similar level of accuracy. This model is parsimonious in that it only uses the primary parameters of each synthetic storm: hurricane landfall location (x_o), heading direction (θ), central pressure deficit (ΔP), radius of maximum winds (R_{max}), and translational speed (V_t). There have been other similar rapid-assessment approaches; our model builds on previous work while expanding the range of storm parameters and improving accuracy.

Primary Reader: Professor Takeru Igusa

Secondary Readers: Professors Benjamin Schafer and Benjamin Zaitchik

Disclaimer

The legal information provided in this thesis about government regulations and the national flood insurance program policies are only an example and have been simplified for the purpose of our modeling efforts. This information may not be accurate or up-to-date and must not be used as a legal reference. Readers should refer to appropriate sources to get accurate information regarding legal issues about flood insurance policies and government requirements for flood prone communities.

Acknowledgements

During my time at Johns Hopkins University, I had the privilege of working under the supervision of two brilliant professors to whom I would like to express my sincere gratitude: my wonderful advisor Professor Takeru Igusa for his endless support and encouragement, whose genius expertise and infinitely positive attitude will always be an inspiration to me; and, my former advisor Professor Robert A. Dalrymple whose deep knowledge and great enthusiasm towards coastal engineering has guided me through my career as a coastal engineer.

I am also grateful to Mr. Sidney O. Dewberry, emeritus chairman and founder of Dewberry LLC, for encouraging me to finish graduate school, along with my colleagues at Dewberry who filled in for me while I was working part time. I owe special gratitude to my amazing manager and mentor Mr. Jeffrey Gangai for his understanding, support, and unconventional instructive guidance towards this research. I also must express thanks to my lab mate Mr. Zhaohao Fu for all his help and support. This work would have not been possible without his extremely helpful insight. Further, I appreciate the support of all my dear friends specially Dr. Majid Maleki without whose help and guidance it would not have been possible for me to apply to an American graduate school and immigrate to the U.S. Finally, I would like to recognize Professors Lian Shen, Seth Guikema, Celso Ferreira, Lingxin Hao, and my thesis committee: Professors Benjamin Schafer and Benjamin Zaitchik.

Last but not least, I would like to thank my incredible amazing husband Michael for his never ending love and support, who also took the time to edit this thesis, my adored daughter Rosa, and my parents and siblings whom I miss dearly. I would also like to thank my wonderful child care provider Mrs. Mahvash Behdinan for working on weekends and providing my beloved daughter with love and care while I was working on my thesis.

This material is based upon work supported by the National Science Foundation under Grant No. 1331399. The support of the sponsor is gratefully acknowledged. Any opinions, findings, conclusions or recommendations presented in this thesis are those of the authors and do not necessarily reflect the view of the National Science Foundation. This work received additional financial support from the civil engineering department of Johns Hopkins University and Dewberry LLC.

Dedication

This thesis is dedicated to my wonderful husband, **Michael**, for his unconditional love and support; my beloved daughter, **Rosa**, for always reminding me how to be a real scientist with her endless curiosity and creative imagination; and to the memory of my dearest mom, **Mahma** who would have been happy to see me follow my dreams.

Contents

List of Tables

List of Figures

Notation

ΔP	central pressure deficit of tropical cyclone, computed as the difference between a far-field atmospheric pressure of 1,013 hPa and central pressure (hPa)
θ	heading direction of tropical cyclone (deg)
V_t	translational speed of tropical cyclone (km/h)
x_o	tropical cyclone landfall location
ABM	agent based model
ADCIRC	advanced circulation model
AEP	annual exceedance probability (yr^{-1})
CCDF	complementary cumulative distribution function
CDF	cumulative distribution function
CHS	coastal hazards system

CLOMR	conditional letter of map revision
CRS	community rating system
DFIRMs	digital flood insurance rate maps
EMV	expected monetary value
FEMA	federal emergency management agency
GKF	Gaussian kernel function
GUI	graphical user interface
HMGP	hazard mitigation grant program
JPA	joint probability analysis
JPM	joint probability method
JPM-OS	joint probability method with optimal sampling
LOMR	letter of map revision
NACCS	north Atlantic coast comprehensive study
NSF	national science foundation
NOAA	national oceanic and atmospheric administration
PBL	planetary boundary layer numerical model
PDF	probability density function
PDM	pre-disaster mitigation grant program

RL	repetitive loss properties
R_{max}	radius of maximum winds of tropical cyclone (km)
SEES	science, engineering and education for sustainability
SFHA	special flood hazard area
SLC	sea level change (m)
SWAN	simulating waves nearshore
TC	tropical cyclone
USACE	United States army corps of engineers
XC	extratropical cyclone

Chapter 1

Introduction

1.1 Motivation and Background

Historically, compared with all other types of natural disasters, coastal flooding has been responsible for the most property damage and the largest number of lives lost in the United States [Hayat et al. 2015]. The U.S. Atlantic coast is subject to repeated hurricane hazards. Tropical storms (e.g. Hurricanes) and extra tropical storms (e.g. Noreaster's) hit the east coast of the U.S. frequently, often causing severe damage to this politically and economically critical area because of its dense population. According to the National Ocean and Atmospheric Administration (NOAA), nearly 40% of the U.S. population lives near the coast. 52% of the total U.S. population lives in coastal watershed counties. The coastal population is expected to increase by 10% by the year 2020 [Burkett et al. 2012]. NOAA lists surge vulnerability facts as the following:

- "From 1990-2008, population density increased by 32% in Gulf coastal counties, 17% in Atlantic coastal counties, and 16% in Hawaii [U.S. Census Bureau 2010].
- Much of the United States' densely populated Atlantic and Gulf Coast coastlines lie less than 10 feet above mean sea level.
- Over half of the Nation's economic productivity is located within coastal zones.
- 72% of ports, 27% of major roads, and 9% of rail lines within the Gulf Coast region are at or below 4 feet elevation [CCSP SAP 4-7].
- A storm surge of 23 feet has the ability to inundate 67% of interstates, 57% of arterials, almost half of rail miles, 29 airports, and virtually all ports in the Gulf Coast area [CCSP SAP 4-7]" [NOAA].

Storm surge, coastal inundation, erosion, and wind damage caused by hurricanes impose devastating impacts on the nation's economy, security and coastal ecosystems. Blake et al. (2011) estimated the direct cost of the top seven most damaging hurricanes, six of which have occurred since 2004, to be over $400 billion. The vulnerability of the coastal communities is intensifying by sea-level changes (SLC) and increasing storminess [NACCS 2015]. In addition to rainfall, storm surge, and waves, which are primarily accountable for coastal flooding, tides can also have a significant influence on the degree of flooding and the extent of the flooded region because of their large amplitude. In October 2012, Hurricane Sandy hit the east coast of the US during a high tide, which enormously amplified the storm surge generated by Hurricane Sandy [NACCS 2015]. Reportedly, when Sandy made landfall on the coast of New Jersey, the full moon increased the tide levels 20% higher than normal; in turn, this increased the total inundation water levels even higher, and caused a major natural catastrophe.

For decision makers and authorities, it would be extremely valuable to be able to predict the possible storm surge elevations and potential imminent disasters before they actually occur, to have ample time for storm preparedness and pre- and post-disaster efforts. In addition to storm surge predictions, increasing coastal resiliency and preparedness for hurricane hazards are of significant importance to reduce the losses caused by coastal storms. To increase coastal resiliency, several involved organizations and agents need to work parallel to one another and collaborate to reach the mutual goal of having more resilient coastal communities. Although these collaborations are already happening in many settings, prior to the current research, no study had been conducted on the nature of these agents' collaborations and their direct- and indirect- relations. We discerned the lack of such system and the importance of studying these agents and their relations as a whole system, which also includes evaluating these agents' socio-economic relations, in a mathematical manner. More details on this matter is provided in the next section and the following chapters.

1.2 Objective

The current study is part of a hazards science, engineering and education for sustainability (SEES) project with the title of: "Modeling to Promote Regional Resilience to Repeated Heat Waves and Hurricanes," funded by the National Science Foundation (NSF). In the present research effort, we have created an agent-based model (ABM) to contemplate the different agents involved in the process as a system and classified different decision makers individually and as separate groups to study how they interact, and how each agent's decisions and behaviors impact other agents.

In our analysis, we consider two levels of decision-making: the most basic is at the individual level in which each homeowner decides on upgrading the flood resistance of their home. The other level is at the community level in which the members of the community must decide to build a measure that would provide community-wide flood protection. There is a natural tension between the individual and community levels since at the community level, each individual homeowner would need to give resources, typically in the form of taxes, to build infrastructure for the benefit of other homeowners. This tension is not unique to flood mitigation or civil engineering, but is also present in almost any decision-making and policy in community building and strengthening. In this thesis, we briefly examine the interplay between community and individual actions using a theory of multi-level interactions from sociology. It is shown how this theory can be applied to community resilience and integrated with agent-based modeling. In this process, it is shown how this may lead to integration with an entirely separate system dynamics approach towards modeling of community resilience.

It is noted that there are two general approaches towards the development of agent-based models. One is to use agents with simple behaviors embedded in an environment with simple properties so that the fundamental interactions can be understood; the other approach is to use agents with complex behaviors in an environment that is characterized by detailed spatial-temporal-societal information in an attempt to simulate a real system.

The thesis addresses both approaches in the following manner. A systems modeling technique is used to define, through a series of closely related diagrams, the primary objects, behaviors, states and activities associated with building resilience and reacting to flood hazards. A conceptual ABM is then developed using these systems constructs. The results at this point can then be used to proceed towards a highly detailed or a simpler, fundamental agent-based model. The remainder of the thesis follows the latter approach, because there is a research need to further understand the fundamentals, particularly at the individual versus the community levels as described above. While the ABM involves multiple players – the homeowners and insurer – the underlying analysis is simpler than what is used in economic equilibrium models [Arrow and Hahn, 1971]. The conceptual ABM presented in this thesis will still be used to inform the development of detailed models in separate, complementary efforts of the NSF project.

This study also focuses on finding rapid methods to predict and assess the magnitude and uncertainty of future flood hazards in the mid-Atlantic region. This knowledge is used to prepare for the negative impacts of those hazards, increase coastal resiliency by proper coastal planning, and implementing appropriate flood control measures. Our probabilistic surge response model predicts flood elevations for potential future hurricanes using a maximum likelihood estimation method, and is fed by previously computed surge heights generated by numerical simulations of hundreds of ADCIRC and SWAN runs of the North Atlantic Coast Comprehensive Study (NACCS) conducted by the United States Army Corps of Engineers (USACE) in 2015.

1.3 Study area

Our storm surge predictor model has been trained with the pre-computed storm surge data from ADCIRC and SWAN runs of the NACCS study in the mid-Atlantic region, more specifically, the open coasts of Anne Arundel County, Maryland. The prediction methodology however, is quite general for coastal areas and can be used at any open coast where surge simulations and synthetic storm data are available.

The agent-based model also is applicable to any coastal community in the United States; with minor modifications, it may also be applicable to coastal communities in other nations with similar flood risk vulnerabilities and flood insurance programs.

1.4 Thesis overview

In Chapter 2 we present our probabilistic model for rapid assessment of storm surge heights. The storm surge simulation data that was used to train the prediction model is also described in chapter two. Chapter 3 introduces the conceptual system model for storm damage and community response scenarios through a series of unified modeling language (UML) diagrams. In Chapter 4 we develop a conceptual agent-based model (ABM) corresponding to the system model in chapter three for coastal flood hazard mitigation plans. In Chapter 5 it is shown how decision theory with uncertainties can be incorporated into the concepts of the preceding two chapters to develop a simplified computational ABM. A parameter study in Chapter 6 demonstrates the visual aspects of the ABM, with graphs that provide insights into the behaviors of the agents of the model. In Chapter 7, it is shown how linear systems theory from sociology can be used to examine the roles of homeowners as individuals protecting their homes and as members of a community with a shared goal of improving resistance to flood hazards in the entire community. Concluding remarks and recommendation for future research are provided in Chapter 8. Appendix A summarizes the synthetic tropical storm parameters data of the subset of the NACCS study to train our storm surge prediction model.

Chapter 2

Probabilistic Method for Rapid Assessment of Storm Surge Heights

2.1 Introduction

During a hurricane, storm surge, depth, and tide are the primary factors responsible for coastal flooding. Storm surge, especially when combined with a high tide, causes increased water levels that can lead to the inundation of coastal areas. From the flood-management perspective, it is of extreme importance to know, and be able to predict, the potential surge levels before the storm makes landfall and flooding occurs. This information can help decision makers to plan for flood protection, and if necessary, evacuation of the area before the hurricane hits the shoreline.

With today's technology, a storm's surge height can be calculated quite accurately by numerical simulations of high-resolution models, such as the Advanced Circulation Model for Oceanic, Coastal and Estuarine Waters (ADCIRC) and the Simulating Waves Nearshore (SWAN), using supercomputers. Nonetheless, these models can take several hours or days to run. Flood managers do not always have the luxury of waiting this long before the storm makes landfall, particularly in hurricane forecasting cases. Hence, it is crucial to be able to predict storm surge heights accurately, and in a timely manner.

As a complement to computationally intensive approaches for estimating storm surge, other researchers have tried to develop more rapid and simpler approaches to achieve similar results [Irish et al., 2008, 2009, 2011; Taflanidis et al., 2012, 2013, 2016]. These methods involve using simulated storm surge data calculated by the numerical models mentioned above, and the application of statistical methodologies for rapid storm surge prediction to assess flood risks. This approach is of particular interest for real-time forecasting. These models, while extremely useful, also come with limitations. For instance, many of these models are only applicable to a single value for the angle of the storm track (track direction, or heading), and/or a specific value of the translation speed of the storm. Thus, if a storm has a different heading direction than the default values of the model, these models cannot be used to predict the surge heights for that specific storm. These models typically are trained by simulated surge heights from hundreds of previously computed ADCIRC and SWAN runs in the area of interest.

In this chapter, we introduce a probabilistic surge response model for rapid assessment of hurricane wave and surge risks in the mid-Atlantic region that uses the maximum likelihood method for flood elevation predictions, with fewer limitations compared to the previous studies. This probabilistic model is trained by the simulated surge height data generated by numerical simulation of hundreds of ADCIRC and SWAN runs in the recent north Atlantic coast comprehensive study (NACCS) of the USACE.

Our model makes these flood elevation predictions in a matter of minutes versus the high-fidelity models that take hours to run, to provide rapid, rough estimates that can serve two purposes: These estimates can help decision makers more quickly understand the extent of potential hazards from each storm. They can also be used as a filter, in the form of a statistical classifier, to determine which storm should be analyzed in more depth.

The model predicts the risk of coastal flooding based on the following primary parameters of the synthetic storms developed by NACCS: hurricane landfall location (x_o), heading direction (θ), central pressure deficit (ΔP), radius of maximum winds (R_{max}), and translational speed (V_t). These parameters are defined in more detail later in this chapter.

In addition to the simulated storm surge data available from the NACCS, there are thousands of other simulated data available from numerical simulations of high-fidelity model runs for the majority of coastal regions in the U.S. that can be used to train the prediction model for the region of interest. These runs were performed by the Federal Emergency Management Agency (FEMA), USACE, and other project partners during the storm surge studies within FEMA's mandate of the analysis of U.S. coastal hazards. FEMA is in charge of preparing Federal Insurance Rate Maps (FIRMs); these maps show the locations of the flood hazard zones in coastal and inland watershed communities in the U.S. In the past few years, with the assistance of USACE and project partners, FEMA has developed and applied a state-of-the art storm surge risk assessment program to update the flood maps to reflect up-to-date, and more accurate floodplain levels. The historical records of the storm events that impacted the region are used in these storm surge studies to develop a synthetic suite of storms and the storm characteristics, and also reconstruct pressure and wind fields to be used as the boundary conditions in the hydrodynamic models [Vickery 2013]. NACCS storm surge studies followed a similar methodology to produce a set of synthetic storms that we have utilized for training our storm surge prediction model. More details on these studies are provided in the next section.

2.2 Review of the North Atlantic Coast Comprehensive Study (NACCS)

Motivated by the catastrophic consequences of Hurricane Sandy, the North Atlantic Coast Comprehensive Study (NACCS) was performed by the US Army Corps of Engineers as a coastal storm hazard and vulnerability risk assessment program for the coastal regions from Virginia to Maine. The water level and wave modeling goals of NACCS was to create a comprehensive reference database required for hazard evaluations to inform future risk reduction projects and contribute to increased coastal resiliency. This reference database was generated by simulating 1,050 synthetic storms, covering a wide range of storm parameters that covers the possible future hurricanes that can impact the study area [NACCS 2015], as explained below.

2.2.1 Hurricane Parameters

Storms are normally described in terms of their primary forcing parameters that affect the storm surge, including the following:

- Track location/landfall location (or, equivalently, the minimum distance from the track to a reference point along the coast): x_o
- Heading direction: θ
- Central pressure deficit (representing hurricane intensity): ΔP^*
- Radius of maximum winds (representing hurricane size): R_{max}

- Translational speed/forward velocity: V_t

  *ΔP is the difference between the central pressure C_P and the far-field atmospheric pressure, which in most cases is assumed to be 1,013 hPa (i.e., $\Delta P = 1{,}013 - C_P$).

These parameters are illustrated in Figure (2-1). The storm parameters are treated as random variables in the joint probability method (JPM) and are used to generate synthetic storms as explained in the next section. The magnitude of the storm surge is predominantly a function of storm intensity, size, and the along-shore distance from the storm center [NACCS 2015].

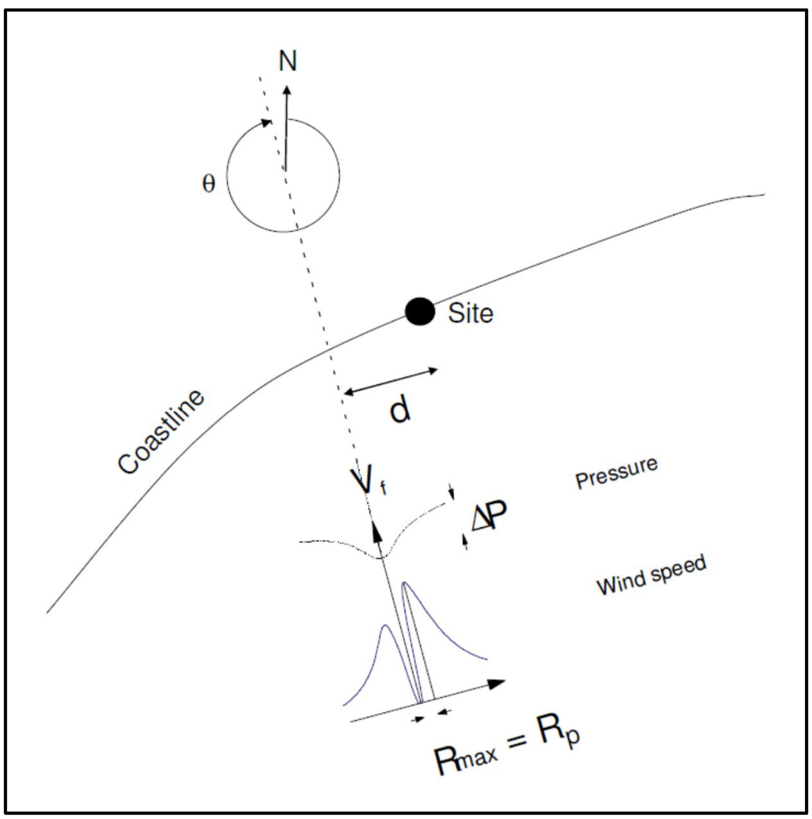

Fig. (2-1): Characterization of a storm as it approaches the coast [Toro 2008].

2.2.2 Development of Synthetic Storms

A joint probability method with optimal sampling (JPM-OS) was used to develop the synthetic storm suite in which the storms were created by a probabilistic model of the storms' primary parameters. Optimal sampling of the joint distribution of the storm parameters generated 1,050 unique synthetic storms. These 1,050 storms covered the region spatially and consist of a wide range of practical hazards by including a wide range of storm return periods [Good 2001, Haan 2002, Hawkes 2002 & 2005, NACCS 2015].

The NACCS study used the NOAA national hurricane center HURricane DATabase (HURDAT2) for the storm parameters of historical storm events that impacted the study area from 1938 to 2013. The values of the storm parameters were marginally discretized as listed in Table (2-1). Some of the storm tracks are shown in Figures (2-2) through (2-5) borrowed from the NACCS "Coastal storm hazards from Virginia to Maine: ERDC/CHL TR-15-5" report [NACCS 2015].

Table (2-1): Discrete values of synthetic storm parameter marginal distributions [NACCS 2015].

Storm Parameters	NACCS Sub-region 3	NACCS Sub-region 2	NACCS Sub-region 1
Heading direction (θ)	-60°, -40°, -20°, 0°, +20°, +40°	-60°, -40°, -20°, 0°, +20°, +40°	-60°, -40°, -20°, 0°, +20°, +40°
Central pressure deficit (ΔP)	From 28 to 98 hPa At 5 hPa intervals	From 28 to 88 hPa At 5 hPa intervals	From 28 to 78 hPa At 5 hPa intervals
Radius of maximum winds (R_{max})	From 25 to 145 km, median of 54 km	From 25 to 158 km, median of 62 km	From 26 to 174 km, median of 74 km
Translational speed (V_t)	From 12 to 59 km/h, median of 27 km/h	From 14 to 88 km/h, median of 45 km/h	From 16 to 83 km/h, median of 49 km/h

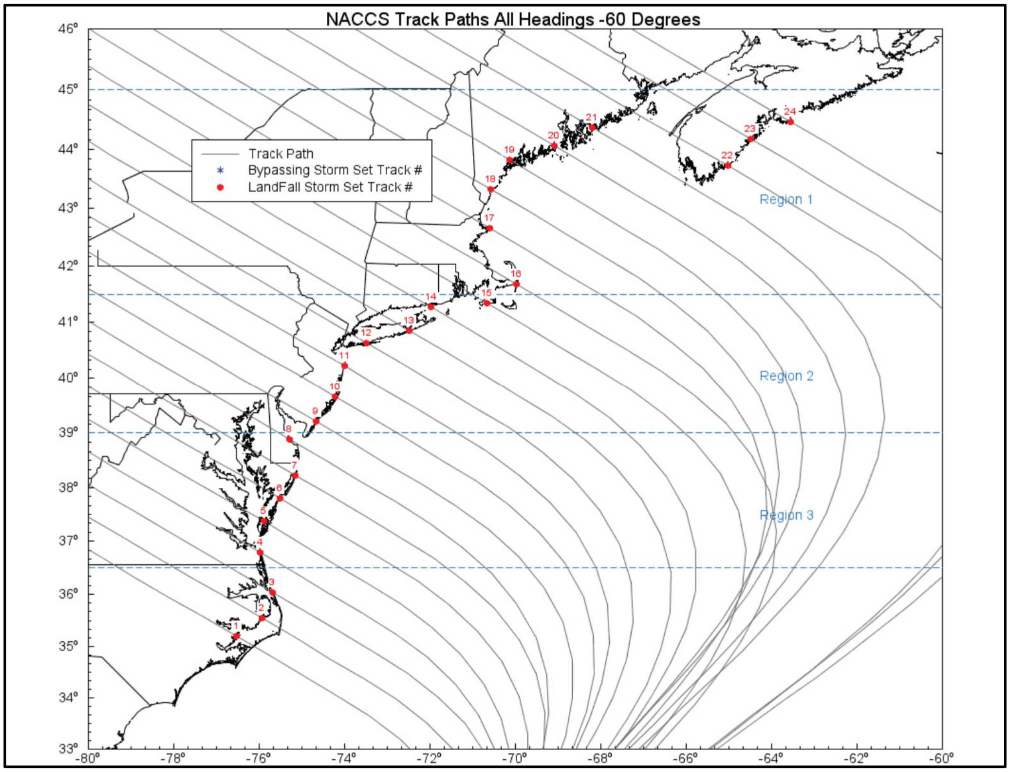

Fig. (2-2): Landfalling -60° master tracks for the NACCS region [NACCS 2015].

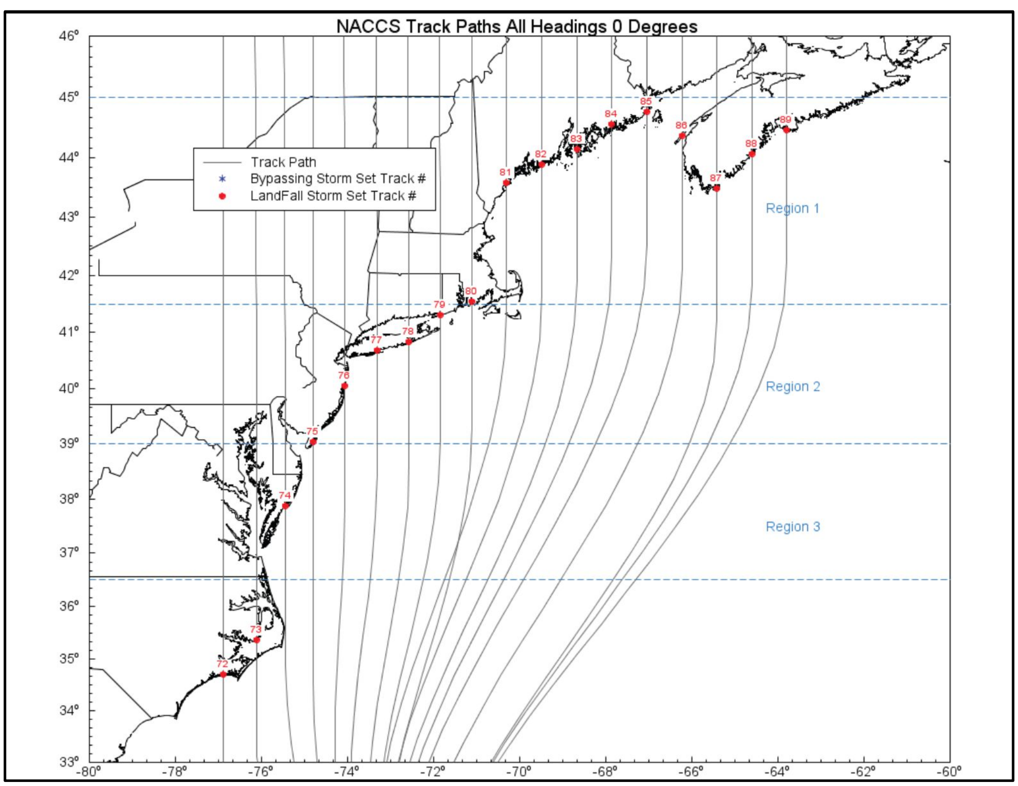

Fig. (2-3): Landfalling 0° master tracks for the NACCS region [NACCS 2015].

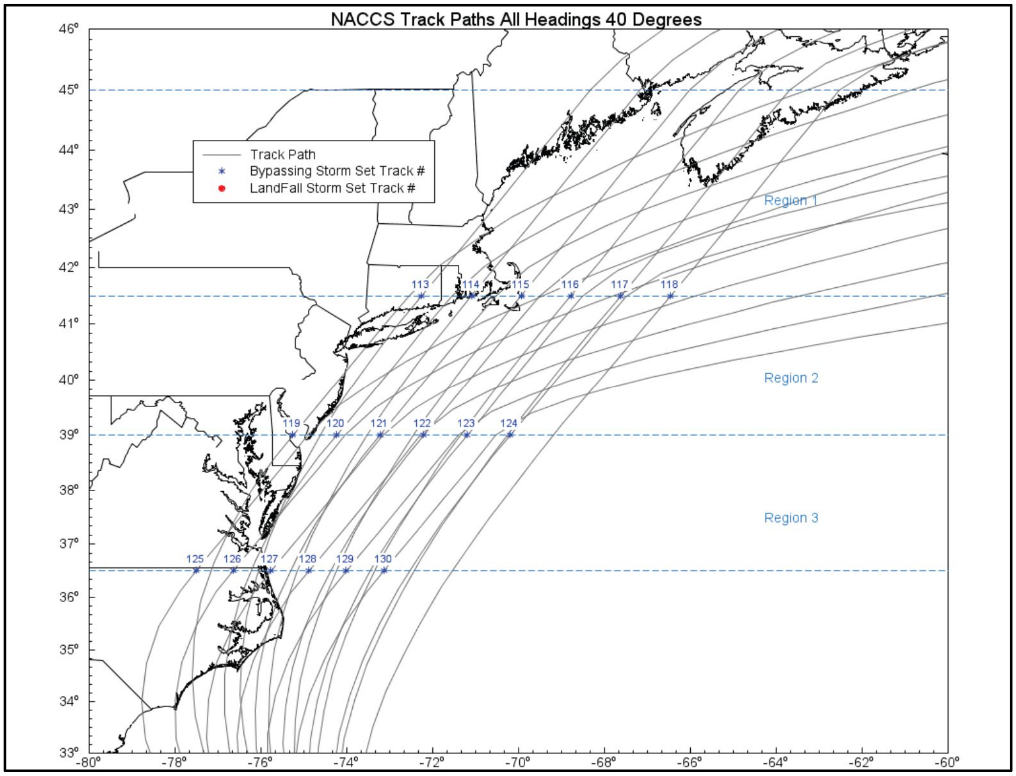

Fig. (2-4): Landfalling +40° master tracks for the NACCS region [NACCS 2015].

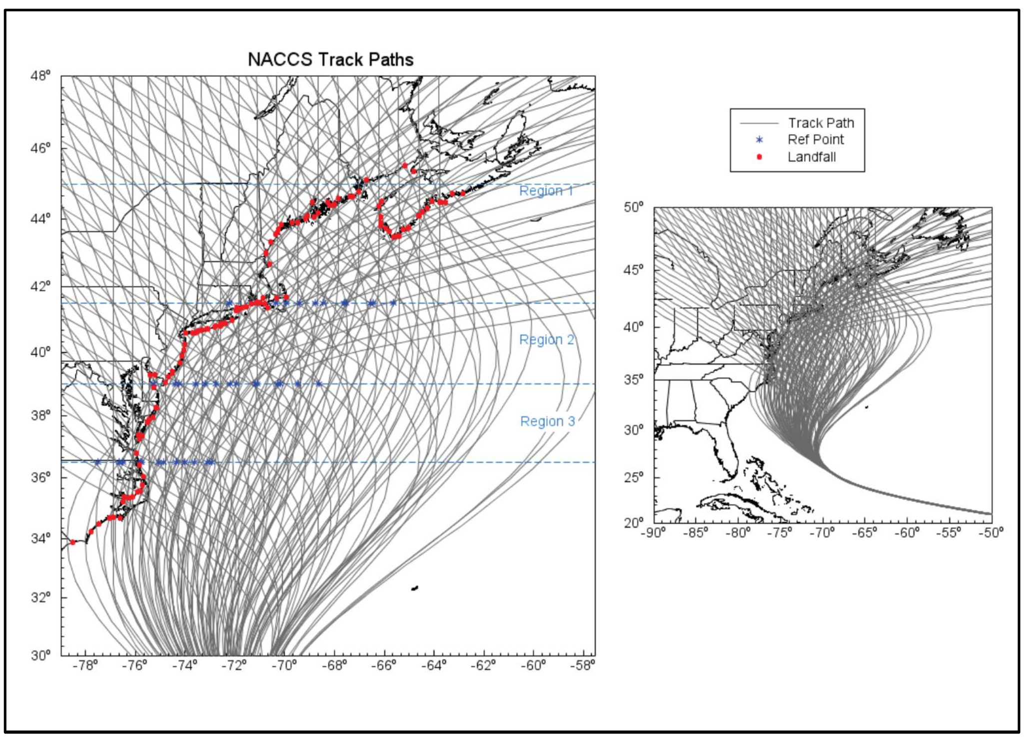

Fig. (2-5): Master tracks (landfalling and bypassing) for the NACCS region [NACCS 2015].

These synthetic storms were then numerically simulated on a high-resolution mesh grid with dense spatial coverage of the near-shore areas using high-fidelity hydrodynamic and climate models. The minimum size of the mesh grid at the near-shore regions was of order of 10 meters. The NACCS project also evaluated the effects of future sea-level changes (SLC) on hurricane hazards. More information about the generation of the TCs can be found in the NACCS "Coastal storm hazards from Virginia to Maine: ERDC/CHL TR-15-5" report [NACCS 2015]. The results of high-fidelity numerical models and computed storm response are stored on the coastal hazard system (CHS) website (https://chs.erdc.dren.mil). These results include storm surge, storm climatology, water level, waves, etc.

CHS provides a storm hazard data storage and mining system, where the data can be easily accessed publicly through a user-friendly graphical interface. The simulated results provided on CHS include the storm response values on nearly 18,000 station locations in the NACCS study region from Virginia to Maine.

2.3 Proposed Methodology

Here, we extend the general framework described in Irish, et al., (2008) to a classification algorithm suited for the Mid-Atlantic states. For the storm characteristics, we use central pressure deficit, ΔP, radius of maximum wind speed, R_{max}, forward speed of the storm, V_t, Holland's B as a measure of the peakedness of the distribution of the storm wind speed (Holland, 1980), and the storm heading direction, θ. These are the primary inputs to planetary boundary layer models that are needed in the computation of wind and pressure fields that were consequently used as input into hydrodynamic models such as the ADCIRC long-wave hydrodynamic computational tool (Luettich, et al., 1992; Westerink, et al. 1992).

We use a spatial profile of the coastal surge that is dependent on the distance, x_o, from a location on the coast that is offset from storm landfall location. We find that the residuals obtained by subtracting the profiles with storm surge are approximately Gaussian with significant spatial correlation. The spatial correlation was found to follow an exponential model. We used maximum likelihood to determine the parameters for the mean spatial profile and spatial correlation.

We began with the following general form for the storm surge ζ, represented as a mean or expected value with an additive Gaussian error term:

$$\zeta = E[\zeta] + \varepsilon \tag{2-1}$$

$$\varepsilon \sim N(0, \sigma^2)$$

Following Irish et al. (2008), we separated the functional form for the mean into two components. The first component is a spatial profile that depended on the distance from landfall, x, and the radius of maximum wind speed, $R_{\max}$. This component had a maximum non-dimensional amplitude of 1. The second component was simply a coefficient, giving the maximum amplitude of the storm surges at all points on the coast. This component was a function of the remaining parameters, the central pressure, C_p, forward speed of the storm, V_t, Holland's B, and the storm heading direction, θ. In summary, the mean storm surge, expressed as a function of the distance from landfall, x, had the following form:

$$E[\zeta(x)] = f_1(C_p, V_t, B, \theta) f_2(x, R_{\max}) \tag{2-2}$$

To obtain the explicit functional forms for f_1 and f_2 and to estimate the model parameters, we began with 348 synthetic storms that impact the open coast shoreline in the mid-Atlantic region, selected from the 1,050 storms generated in the NACSS study. The parameters of these 348 storms are provided in Appendix A. We then considered only a subset of 20 storms that crossed the open coast shoreline in Northern Virginia or the Delmarva Peninsula. There are 69 stations along this portion of the mid-Atlantic region, leading to a total of 1,380 surge heights for 20 storms at these stations.

It was found that the surge height, as a function of the distance parameter x, generally exhibited a peak near landfall, as expected. Some samples of this relationship between surge height and distance can be seen in Figure (2-6) below. We follow Irish et al. (2009) and use non-dimensional analysis along with an inspection of the surge height – distance relationship observed in the synthetic storms to arrive at the following explicit form for the spatial component, f_2:

$$f_2(x, R_{\max}) = 1 - b_4 \left|\frac{x - R_{max}}{R_{max}}\right| \tag{2-3}$$

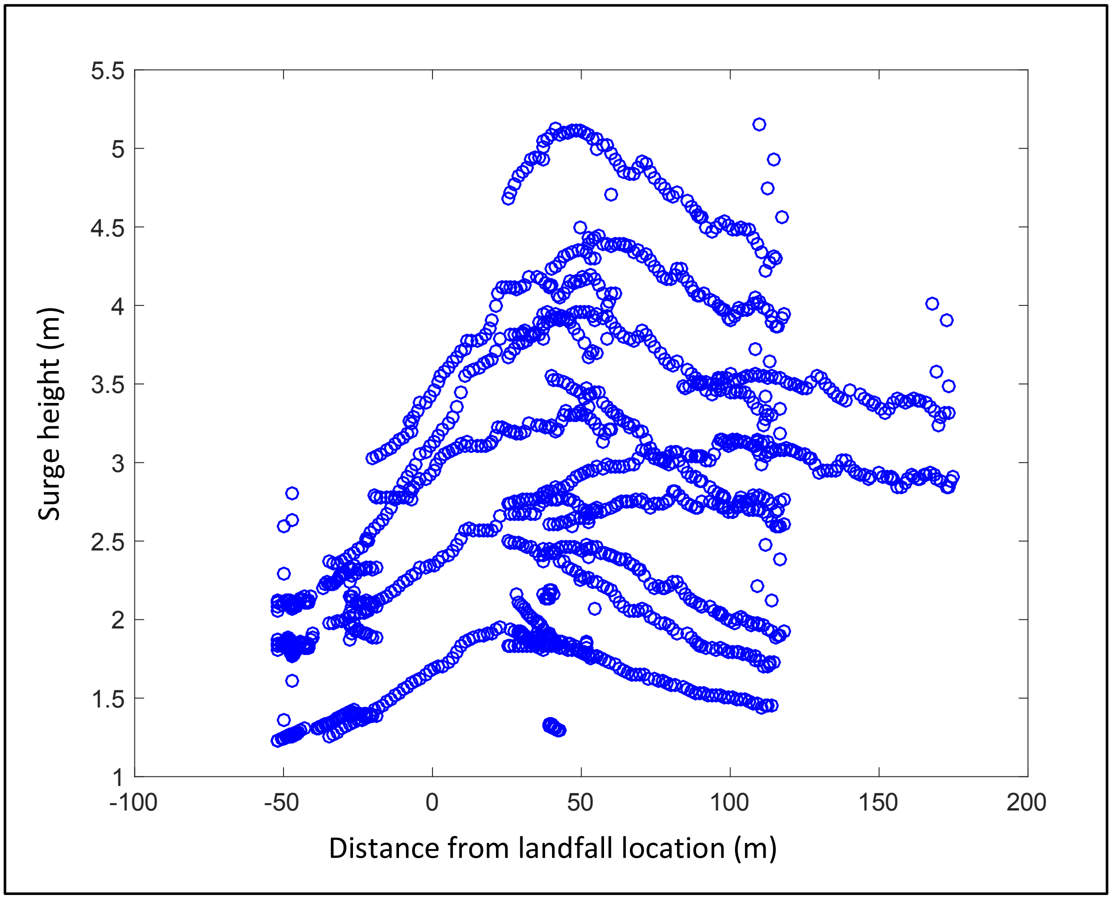

Fig. (2-6): Relationship between storm surge height and distance from storm landfall location.

For the amplitude component, we considered a wide range of polynomials of the parameters C_p, V_t, B, θ and found that only the terms associated with the central pressure C_p and the storm velocity V_t were significant. The final form for the amplitude component is:

$$f_1(C_p, V_t) = (b_0 + b_1 C_p)(b_2 + b_3 V_t) \tag{2-4}$$

Which leads to the expression for the mean surge height:

$$E[\zeta] = (b_0 + b_1 C_p)(b_2 + b_3 V_t)\left(1 - b_4 \left|\frac{x - R_{max}}{R_{max}}\right|\right) \quad (2\text{-}5)$$

We used the maximum likelihood principle to determine the parameters and arrived at the result.

$$E[\zeta] = \left(0.920 + 0.0227C_p\right)(0.000582 + 0.120V)\left(1 - 20.0\left|\frac{x - R_{max}}{R_{max}}\right|\right) \quad (2\text{-}6)$$

With an error term with RMS of σ = 0.320m.

We also tried a more complex model for the error term to account for spatial correlation. The model for surge height was expressed in terms of a mean surge height with two additive noise terms, a term $\delta(x)$ that was dependent on the distance from landfall variable x, and a non-spatially dependent noise term ε. Both noise terms were Gaussian with zero mean and constant variances; the first noise term was also autocorrelated, with correlation that was a function only of the distance $|x_1 - x_2|$ between two surge-height locations. The basic functional forms are as follows:

$$\zeta(x) = E[\zeta(x)] + \delta(x) + \varepsilon \quad (2\text{-}7)$$

$$\left(\delta(x_1), \delta(x_2)\right) \sim N\left(0, C(|x_1 - x_2|)\right)$$

$$\varepsilon \sim N(0, \sigma^2)$$

We experimented with several forms for the spatial correlation. An example is the commonly used exponentially decaying correlation

$$C(d) = C_0 e^{-d/d_0} \quad (2\text{-}8)$$

With correlation length d_0 that leads to the covariance matrix

$$\Sigma = \begin{bmatrix} C_0 + \sigma^2 & C_0 e^{-d_{12}/d_0} & \dots & C_0 e^{-d_{1n}/d_0} \\ C_0 e^{-d_{12}/d_0} & C_0 + \sigma^2 & \dots & C_0 e^{-d_{2n}/d_0} \\ \vdots & \vdots & \ddots & \vdots \\ C_0 e^{-d_{1n}/d_0} & C_0 e^{-d_{2n}/d_0} & \dots & C_0 + \sigma^2 \end{bmatrix} \qquad (2\text{-}9)$$

For points $x_1, x_2, \ldots, x_n$, in which $d_{ij} = |x_i - x_j|$. The corresponding likelihood function is:

$$\mathrm{L}(\zeta_1, \zeta_2 \dots \zeta_n) = \prod_{i=1}^{n} \frac{1}{\sqrt{2\pi|\Sigma|^2}} \exp\left\{-\frac{1}{2}(\zeta_i - E[\zeta])^{\mathrm{T}} \Sigma^{-1} (\zeta_i - E[\zeta])\right\} \qquad (2\text{-}10)$$

Although several candidate forms were used to model the spatial correlation, these relatively complex models produced similar prediction errors as the simple one-term error model. Hence, the model in equation (2-6) is our proposed model for storm surge heights along the open coast shoreline in the mid-Atlantic region.

2.4 Model Calibration and Verification Results

Here we provide a summary of the calibration and verification results of the model shown in equation (2-6). The 1,380 storms surge heights for 20 storms at the 69 stations along Northern Virginia and the Delmarva Peninsula were divided into two sets of 690 data points each, where each set corresponded to 10 randomly selected storms. The results for the surge heights, as a function of the distance to landfall, x, are shown in the top plot of Figure (2-7) with the original synthetically generated data in blue and the rapid estimate in equation (2-6) in red. An alternate comparison between the data and rapid estimate is shown in the bottom plot of the figure, in which the horizontal axis is the original synthetically generated data and the vertical axis is the estimate in equation (2-6). In both plots, it can be seen that the estimate closely tracks the data.

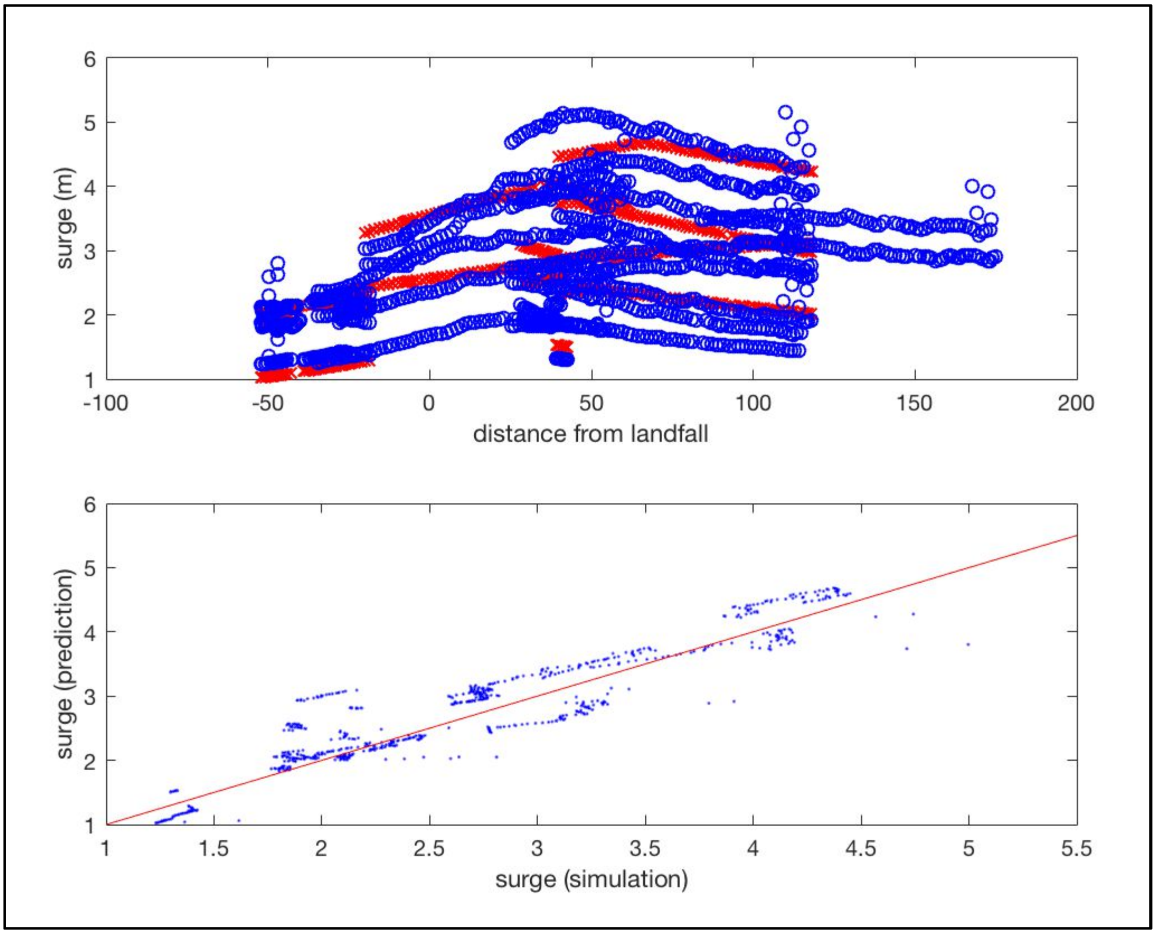

Fig. (2-7): Comparison of the rapid estimate from equation (2-6) with the NACCS results for surge height using 10 out-of-sample synthetic storms.

In a more challenging test of the rapid surge height estimate, we used the data from the Delmarva stations for training and the data from the Northern Virginia stations for validation. The results, shown in Figure (2-8), indicate less accuracy in using out-of-sample stations as compared to using out-of-sample storms that were used in Figure (2-7). Nevertheless, for the out-of-sample stations, the estimates corresponding to surge heights that were above 1.5 meters tended to be conservative, with predicted surge that were generally higher than the NACCS simulated surge.

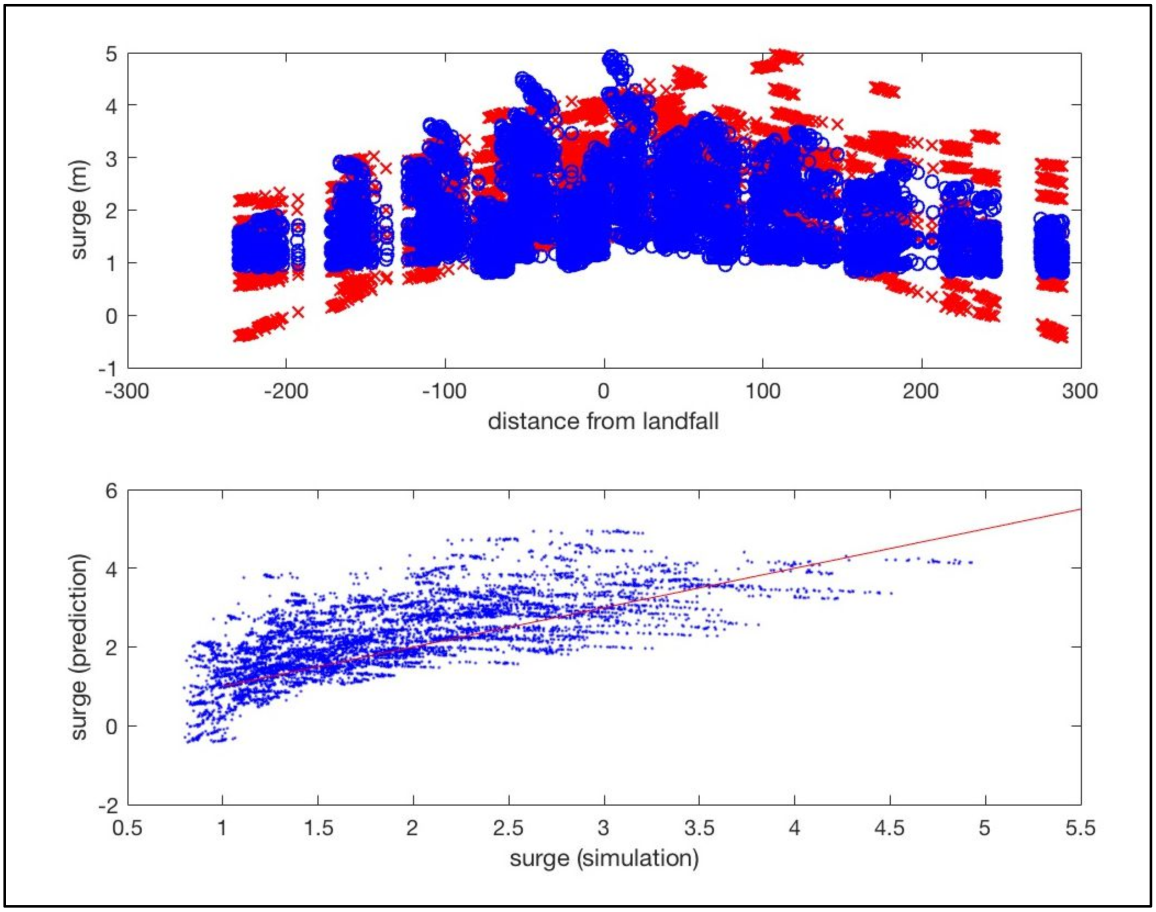

Fig. (2-8): Comparison of the rapid estimate from equation (2-6) with the NACCS results for surge height using out-of-sample stations (along the coast of Northern Virginia).

Chapter 3

Systems Model for Storm Damage and Community Response Scenarios

3.1 Motivation and Background

In this chapter we develop a conceptual systems model that can be used to describe the scenario that develops in a community that is subject to storm hazards. Our interest is on examining the interactions between the major actors in the community, beginning with homeowners and extending to community government, insurers, planning engineers, and businesses. We are also interested in long durations, where repeated storms can occur, and where both short-term and long-term behaviors must be included.

There are a variety of conceptual systems modeling techniques that can be used. For instance, causal loop diagrams have often been used for showing interactions and influences between players/stakeholders of a system. This type of model has been particularly useful for public health investigations, in which it is necessary to trace the cause of undesirable or unhealthy behaviors. Such causal loop diagrams can then be used to develop programs to intervene at strategic points of the system to reduce or stop these behaviors. The primary motivation for developing causal loop diagrams is to gain a clear understanding of the root causes of unwanted behavior.

For the storm hazard scenario, the behavioral aspects are straightforward and well understood. For instance, there are physics-based models that can be used to explain why a home will suffer damage from a storm surge or high winds. Also, processes such as insurance reimbursement for damage to insurance-covered properties are straightforward. Benefits of physical interventions in the form of upgrades at the residence or community levels are relatively easy to assess.

Nevertheless, the combined short- and long-term scenarios of community response to a hazardous environment is complex because of the many interacting sequences of actions that are generated by the storms. For instance, there is a trade-off between individual expenditures on interventions at the residence level versus collective expenditures on interventions to protect entire communities. There are also unintended consequences on some interventions, such as insurance that make it feasible for homeowners to stay in residences in hazardous but desirable seaside sites.

There has been very limited work on systems models for this type of scenario. Studies in this field are usually focused on predicting the outcomes of planning and rescue programs for flood events [Birkland 1997, and Hawe 2012].

This study, however, is focused on the civil engineering point-of-view, including the modeling of a series of actions in mitigation plans towards coastal resiliency, e.g. implementing structural or non-structural flood control measures, and the process of repair and upgrade of private and public properties after flood damage.

Here, we will be developing a conceptual systems model based on the Unified Modeling Language (UML). This type of model is highly expressive, giving multiple perspectives of system interactions in terms of:

- The major actors and components of the system,
- The processes that develop over time,
- The states of the components, which change due to the hazards and the actions of the major actors, and
- The internal processes within each of the decision makers in response to changes in state of the system components.

It is noted that the last property of UML has some similarities to the causal loop diagram, where the causal relationships are between the states of the system components and the decisions made by the decision-making actors.

While the UML diagrams are useful in themselves in producing multiple, complementary views of system operation, their primary purpose is to build object-oriented computational models. In this chapter, we will be introducing some of the major concepts in UML and will develop, in a progressive manner, a systems model for coastal storm resilience. As may be expected from the modelers' perspective, the construction of a UML is far easier than the development of the associated computational model. As noted in the introduction, this thesis will be presenting simple agent-based models so that the fundamentals of the interactions, particularly between the individual homeowners and community can be better understood. Hence, while the model will include a number of detailed features that can be used in the development of quite complex ABMs, only a subset of these features will be used in the ABMs in this thesis.

3.2 Introduction to Unified Modeling Language (UML)

The Unified Modeling Language was first established in 1994-95 by Gary Booch and his team as a general purpose modeling language in the software engineering field. Since then, UML has been revised several times. The main goal of UML is to simplify and facilitate system modeling by better visualizing of the system through a series of diagrams [Booch, 2005]. It has been used extensively in computer science for developing large software systems. It has also been expanded into the Systems Modeling Language (SysML) to incorporate concepts needed for developing other types of technologies that go beyond software and that require the use of systems concepts. These include aerospace, national defense, and other large-scale systems, as well as much smaller, highly complex systems such as cell phones.

In this chapter, we only use the following subsets of UML diagrams and associated concepts that are needed to develop the computation model of the next chapter:

3.2.1 Activity diagrams

These are used to describe the sequence of events that occur in the system. They show the actions or events that are required to change the states of the system components.

3.2.2 Class diagrams

Also known as "block definition diagrams," these define the components of the system and are composed of the following elements:

- **Classes**: representations of the components and actors of the system.
- **Properties**: internal characteristics of the classes.
- **Methods**: also known as "verbs," are actions that are performed by the class on itself or on other classes.

3.2.3 State diagrams

State diagrams demonstrate different states that a component of the system may have during each stage of the process. For instance, after a flood event occurs, a property that is located in the flood hazard area might be at a "damaged" or "undamaged" state.

3.3 Development of UML Diagrams and Concepts for Storm Hazards at the Household and Community Levels

We develop our UML progressively, beginning with the simplest model, and adding features as needed to describe the temporal and homeowner- versus community-level interactions that are needed to characterize coastal storm resilience.

3.3.1 Short-term Scale Events

Our simplest, most abstract scenario operates at the short-time scale for one single storm event on an individual property. UML diagrams for this case are provided in this section. We gradually add more parameters to this simple scenario to build up our model for more complex and detailed scenarios.

3.3.1.1 Activity Diagram for Short-term Event

The activity diagram for the short-term event is shown below, in Figure (3-1). Here we begin at the left, where the filled dot designates the start of the sequence of activities. We then follow the horizontal sequence shown in grey boxes connected by dashed arrows, which is at the heart of this activity diagram. We will subsequently examine the unshaded boxes at the upper part of the diagram.

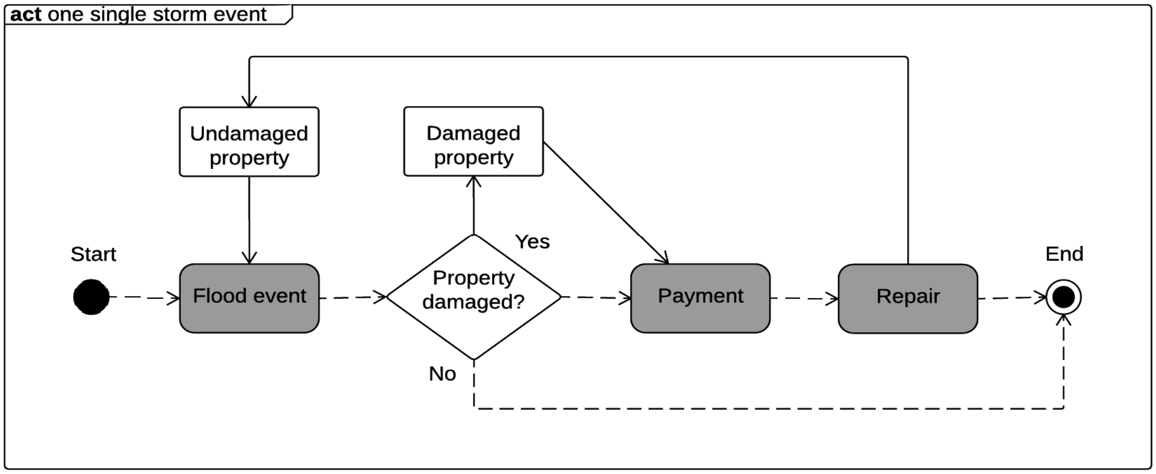

Fig. (3-1): Activity diagram of a single storm event on an individual property.

Following the dashed arrows, we come to the first action, which is the flood event. Continuing on this horizontal sequence of activities, the dashed arrow leads to the decision block in which the property is damaged, or not damaged. If the property is not damaged, no further action is required. Hence, the dashed arrow leads to the terminal point where the activity sequence ends. If the property is damaged, the next action is some sort of payment, which then leads to repair before terminating at the end point of the sequence of activities.

The upper two unshaded boxes represent the states of the property that are directly influenced by the sequence of activities in grey. The initial state of the property is undamaged, as shown in the upper left. After the event, the decision block indicates that the state of the property may change to the damaged state. If this state occurs, then the payment will lead to repairs, which then returns the property back to the undamaged state.

This activity diagram shown in Figure (3-1) is for an abstract property and payment. In the next two activity diagrams, we show how the sequence of events would appear for the special, but obviously important cases where the property is a house or an entire community.

When the property is a house, then, as shown in the next diagram (Figure 3-2), the only difference with the previous, more abstract, activity diagram is in the labels. For instance, the payment is now relabeled as "NFIP payment" which represents the payment from the National Flood Insurance Program (NFIP) to the homeowners towards the repair of the damaged house, assuming the house is covered by flood insurance. It should be noted that homeowners whose properties are located in areas prone to repeated flood damage, known as repetitive loss properties (RL), are required by the NFIP to repair and upgrade their houses to the 100-year flood event protection level [King 2005, and Dixon 2006]. This is embedded in the "repair" box in the activity diagram in Figure (3-2). We will elaborate on this in the next section where repeated events are discussed. Here, by contrast, we are talking about a more general case and are looking at one single storm event only.

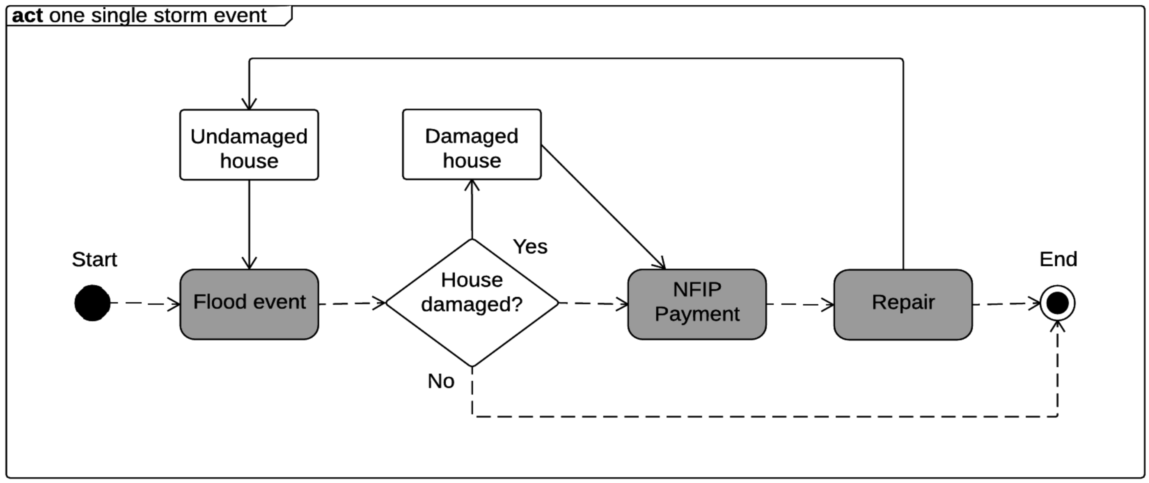

Fig. (3-2): Activity diagram of a single storm event on an individual private property (e.g. a house).

When the property is an entire community, then there are two pathways for the activity diagram that begin at the vertical bar immediately to the right of the flood event (see Figure 3-3). The top pathway is similar to the activity diagram for the house (see Figure 3-2), except that all of the houses in the community are represented. There will be some houses with damage and subsequent NFIP payments, and others with no damage. As before, the "repair" box includes repair and upgrade to a 100-year flood event protection level. The bottom pathway is new, and designates the sequence of activities associated with public areas (including infrastructure). The major difference in the bottom pathway is the type of payment, which is in the form of a post-disaster mitigation grant through the Hazard Mitigation Grant Program (HMGP) from a federal government agency. Normally, local communities are in charge of taking action towards the repair and restoration of damaged public areas and infrastructure after a flood event. It is common that local governments or communities receive funds from the federal government for such repairs through programs like HMGP [FEMA 1999].

There are other important differences between the upper and lower activity pathways in Figure (3-3), and these will be addressed in the other UML diagrams. The block definition diagrams and the state diagrams for the case of one single storm event on a community are shown in Figures (3-4) and (3-5), respectively.

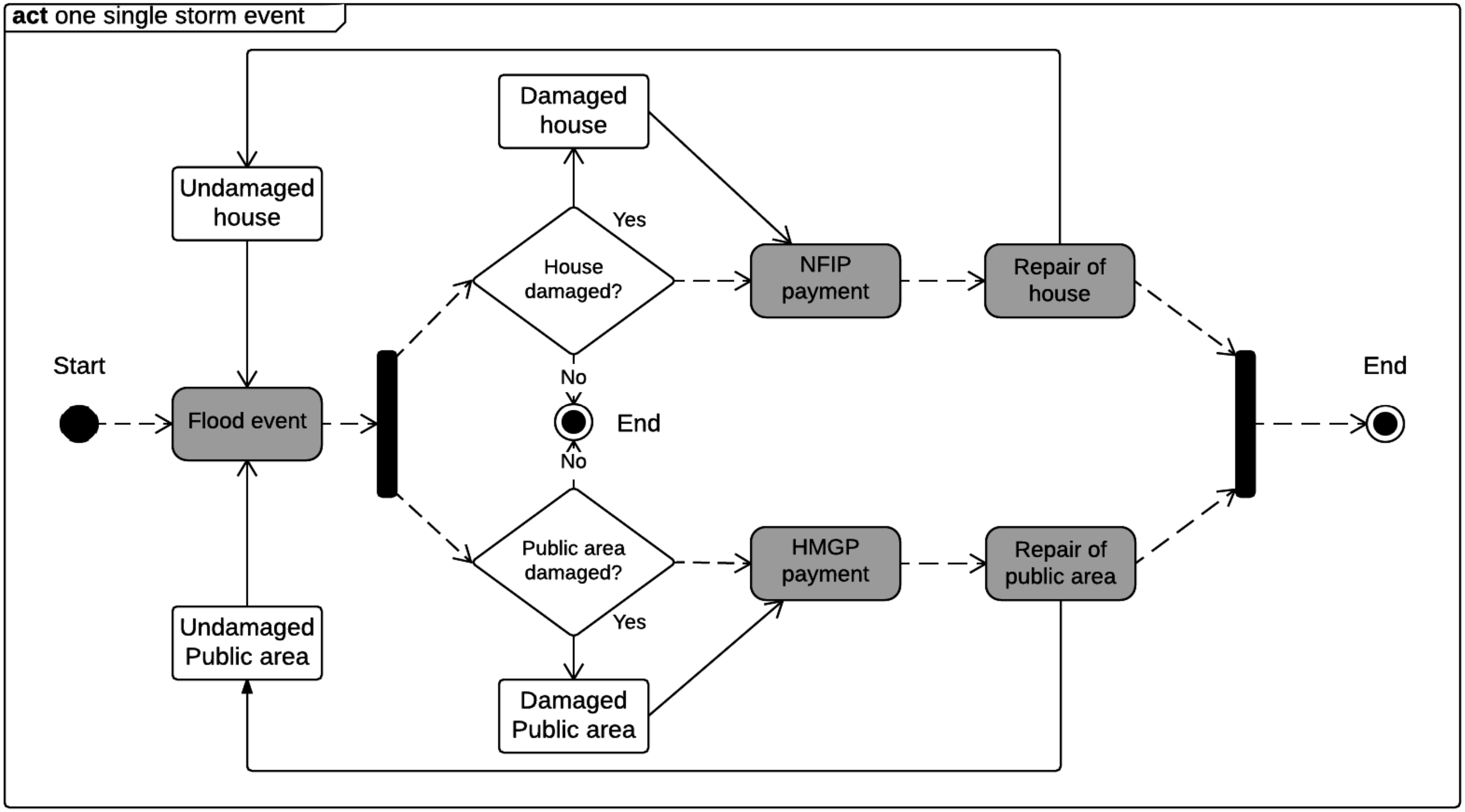

Fig. (3-3): Activity diagram of a single storm event on an entire community.

3.3.1.2 Block Definition Diagram for Short-term Event

The block definition diagram (class diagram) for the short-term event shown in Figure (3-4) represents the model agents and the interactions between the model agents. Each block in the block definition diagram consists of three cells. The top cell contains the name of the agent/class. The middle cell shows the features and properties of the agent. The bottom cell includes the agent's behavior, which are referred to either as verbs, or as methods or actions that the agent performs on itself or other agents. The dashed arrows connecting the locks shows which agents are directly interacting with one another and specifies the relations between the blocks. These connecting arrows/lines are of different pre-defined shapes in SysML, depending on the nature of the connection between the blocks. For instance, —▷ is used to show an "inheritance" relation between two blocks; and —◇ shows "aggregation" [Booch, 2005]. In our model, we only use the dashed arrow - -> to connect the blocks to indicate which agents "affect" other agents as described in more detail below. We begin by describing each class/block in the block definition diagram shown in Figure (3-4).

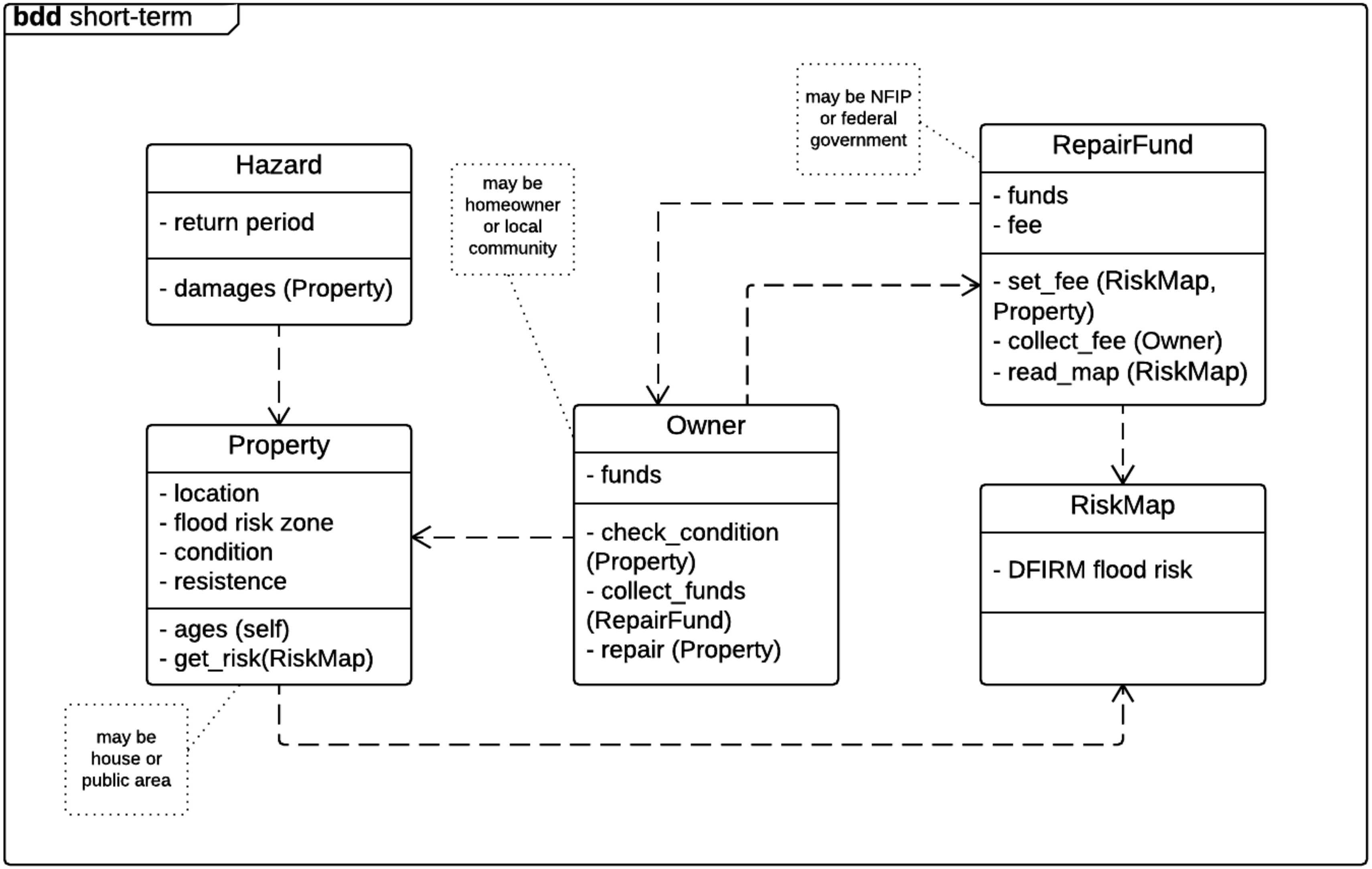

Fig. (3-4): Block definition diagrams for a single storm event on a community.

Hazard

This agent represents the flood event, which has the following features.

Properties: Return period

Shows the strength of the storm event; larger, more severe events are less frequent. For instance, a 500-year flood is a flood with a magnitude that has a 0.2% chance of occurrence each year and which, on average, occurs once every 500 years; it is larger than a 100-year flood which has a 1% chance of occurrence each year.

Verbs: Damage

This is the action of the hazard on the "Property" agent.

Property

This agent may represent a private residential "house" or a "public area" in different parts of the model. Both private and public properties share the following features and verbs; therefore, they are classified here as one agent called "Property."

Properties/features: Location, flood risk zone (according to the flood maps), condition (damaged or undamaged), resistance (degree of resistance against flood)

Verbs: Ages (an action on itself that causes gradual degradation), gets risk (another action on itself that is obtained using risk factor information from the "Risk Map" agent).

Owner

This agent may represent the owner of a private property who is a “homeowner” or the “local community” who is responsible for the public areas and the community as a whole. The following features and verbs are shared between homeowners and local communities and they are classified in this model as the “Owner” agent.

Properties: Funds.

A representation of the available funds of the owner, e.g. the savings or discretionary funds of a homeowner.

Verbs: Checks condition (of the property), collects funds (from the “Repair Fund” agent after a flood damage), and repairs (the Property after flood damage).

Repair Fund

This agent denotes the agent responsible for providing funds to the “owners” to repair damaged “properties” after a flood event. In the case where the “Property” is a house and the “Owner” agent is the homeowner, the “Repair fund” stands for the national flood insurance program (NFIP) which pays repair funds to its policyholders via insurance claims. Similarly, when the “Owner” is the local community and the “Property” is a public area, the “Repair fund” will be the federal government which provides local communities with repair funds through the hazard mitigation grant program (HMGP) to repair damaged public areas and infrastructure. The following features and verbs are shared between the NFIP and the federal government and they are classified in this model as the “Repair fund” agent.

Properties: Funds, fees.

The Repair fund agent has some available funds, and a set rate for fees to be collected from the "Owner" agent. These fees are in the form of flood insurance premiums collected form the homeowners when the "Repair fund" agent is the NFIP and are in the form of taxes collected from local communities and the residents when the "Repair fund" is the federal government.

Verbs: Sets fees (for the "Owner" agent, using the "Risk Map" agent which shows the flood risk of the "Property"), collects fees (from the "Owner"), and reads maps (using the "Risk Map" agent, to define the fee rates for the "Owner").

Risk Map

This agent helps the "Repair fund" agent to set the appropriate fees for the "Owner" by showing the risk of flooding of each "Property." For instance, properties located in flood zones with higher risk of flooding pay higher flood insurance premiums.

The "Risk Map" agent may represent the digital flood insurance rate maps (DFIRMs) which divide the community map into different flood zones with different risks of flooding, or are criteria for defining reduced premiums for upgraded "Properties" depending on the level of upgrade. The latter is addressed later under the long-term event block definition diagram (Figure 3-7) where we cover the subject of the upgrade of the properties. The reduced premiums for upgraded "Properties" also include the reduced premiums offered to participating communities in the community rating system program (CRS) which is described in chapter 4.

Properties: DFIRM flood risk maps

Flood insurance rate maps define the flood zone for each property.

3.3.1.3 State Diagram for Short-term Event

The state diagram (Figure 3-5) for the short-term event includes the states that the classes may have during the course of actions shown in the activity diagrams above (Figures 3-2 and 3-3). While the state diagram shows the possible states of the classes, it does not imply that the class will necessarily go through all of the states shown. It is also noted that each class may be in only one state during each step of the activity diagram.

As mentioned in the previous section, a house may be in one of two states: “undamaged” before the flood occurs or “damaged” after being flooded. It may remain in the “undamaged” state after a flood event. If the house gets damaged during a flood event, it may move back to the “undamaged” state by getting repaired by the home owner. Similarly, public areas may be in the “undamaged” state before the flood happens, move to the “damaged” state after a flood event, and move back to the “undamaged” state after being repaired by the local community. The house or public area may stay in the “undamaged” state after a flood event if the storm is not too strong.

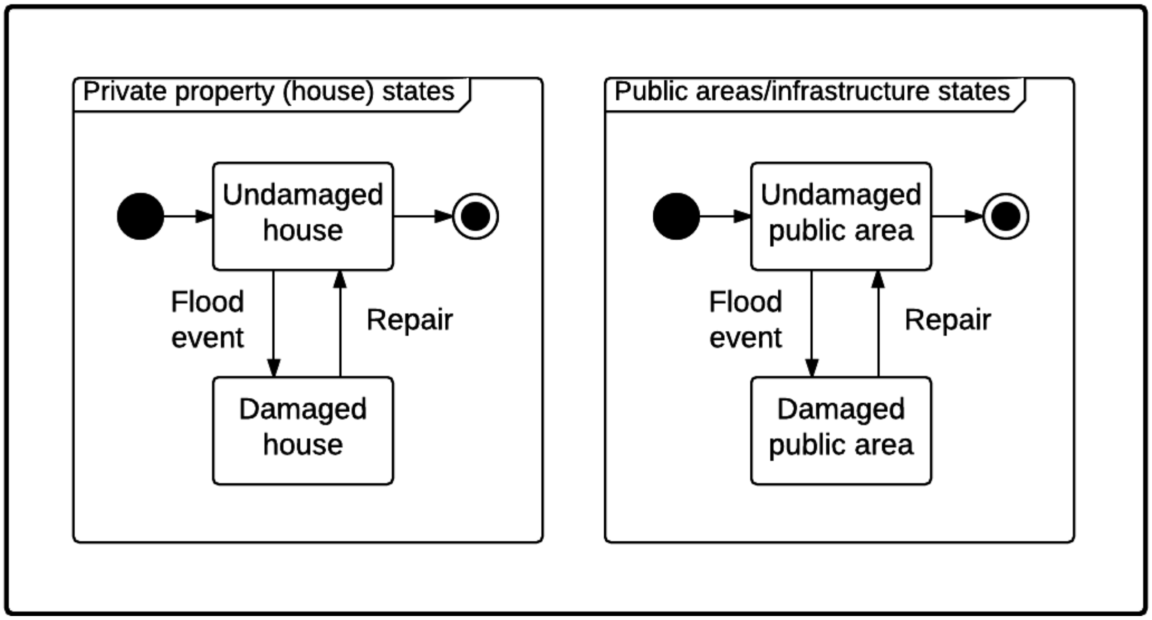

Fig. (3-5): State diagram for a single storm event on a community.

3.3.2 Long-term Scale Events

The UML diagrams presented in this section model community responses to repeated storm events. These diagrams are in part similar to the previous diagrams which model one single storm event. In addition to what was shown in the short-term event model diagrams in the previous section, the long-term event diagrams in this section also include actions that different model components may take to make the community more resilient towards future storm events. These actions can be on a small scale at the level of an individual private property (e.g., a small upgrading project) or on a larger scale to protect the entire community against future hazardous events (e.g., adding a flood control measure).

3.3.2.1 Activity Diagram for Long-term Events

Figure (3-6) demonstrates the sequence of activities for the case of repeated storm events in a community, including the addition of a flood protection measure by a local community to mitigate flooding hazard from future storm events. Such a measure protects a community against storm surge.

We begin from the starting point on the left-hand side and move horizontally to the right. The first section of this diagram shows the sequence of activities for one single storm and is almost identical to the previous activity diagram shown in Figure (3-3). There are two pathways. The top pathway refers to actions related to private property (e.g., houses) and the bottom pathway shows the activities associated with public areas. Up to this point, the only difference between this activity diagram (Figure 3-6) and the previous activity diagram (shown in Figure 3-3) is that the present diagram does not end after one single storm event where the two pathways merge in Figure (3-3). Here, we are interested in the long-term events and the actions the residents (homeowners) and the local government/community would potentially take to prepare the community for future flood events by making it more resilient.

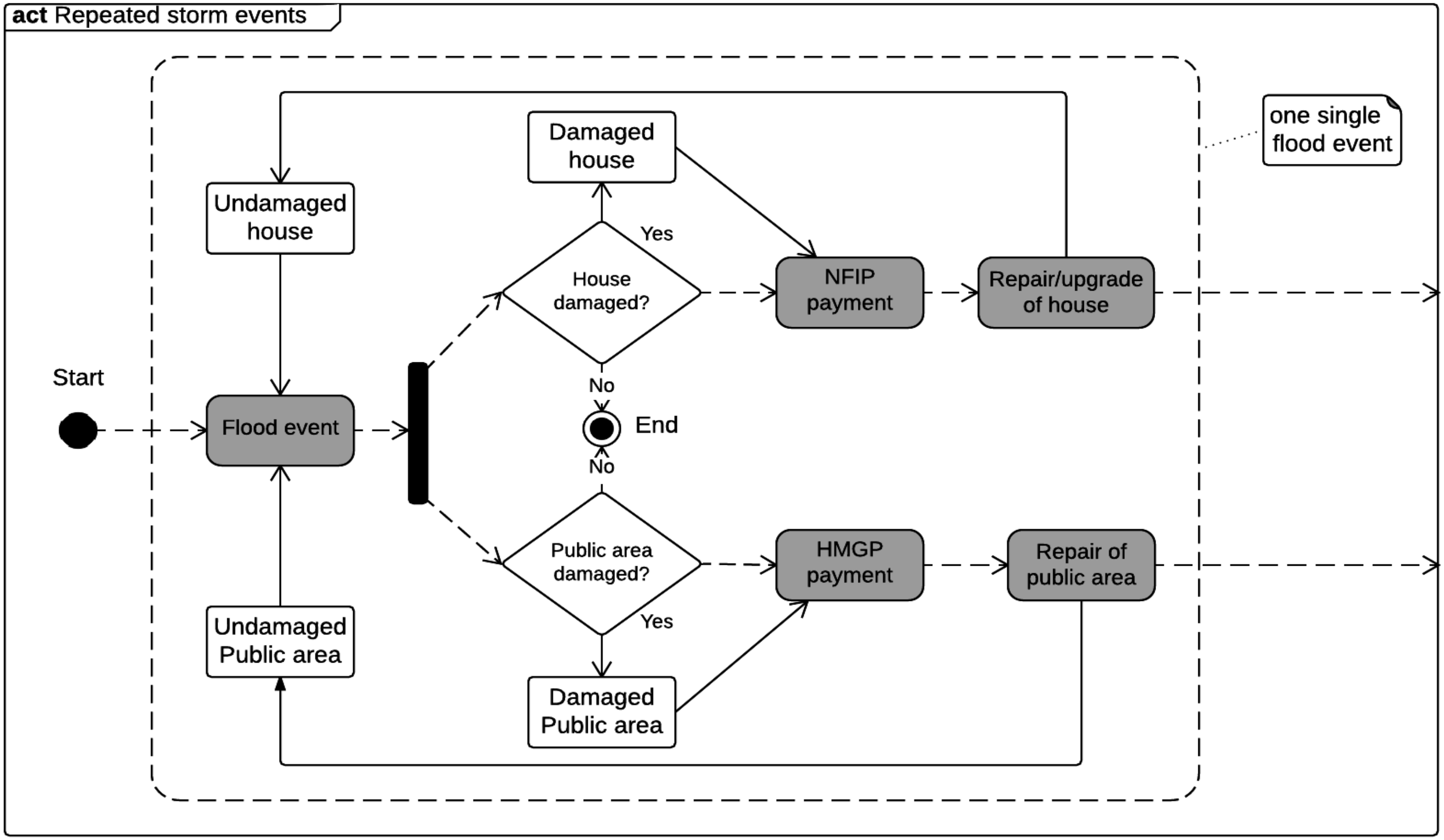

Fig. (3-6): Activity diagram of repeated storm events on a community (continued on next page).

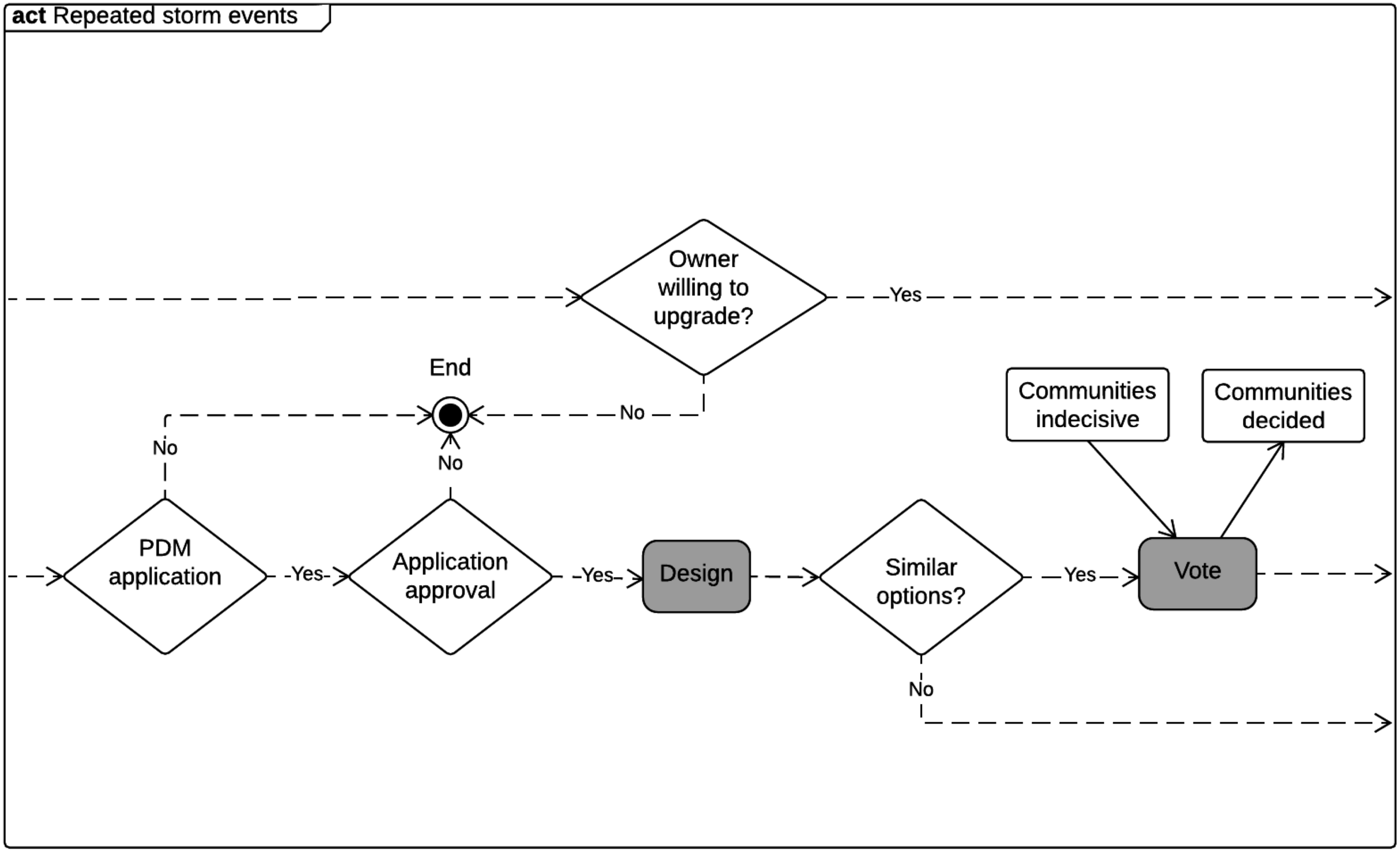

Fig. (3-6): Activity diagram of repeated storm events on a community (continued).

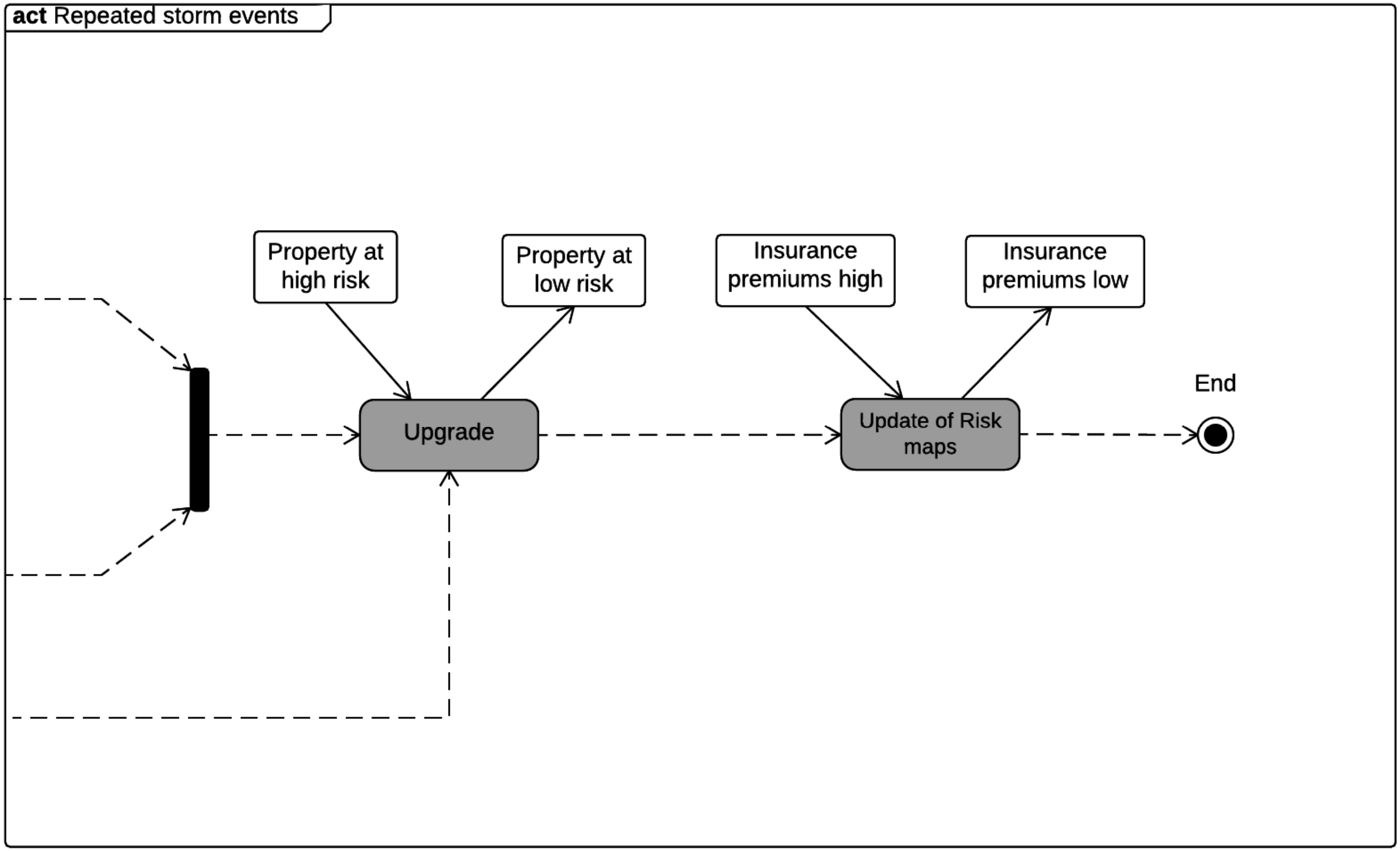

Fig. (3-6): Activity diagram of repeated storm events on a community (continued).

In the top pathway, the last action block at the end of the “one single flood event” box is slightly different from the same block in Figure (3-3). This block has been replaced by “Repair and upgrade of the houses” to include the upgrade of damaged houses to the 100-year flood protection level according to National Flood Insurance Program (NFIP) requirements for repetitive loss properties (RL). This action was embedded but not shown in Figure (3-3) because the upgrade to the 100-year flood protection level regulations refers to repetitive loss as a result of multiple storm events; in the short-term activity diagram we are interested in only one single storm event.

Following the dashed line on the top pathway, there is a decision block which determines whether or not the homeowner is willing to upgrade their house to the next level of protection, which means enough protection to qualify for a reduction in flood insurance premiums. If the answer is no, the activity diagram ends. If the answer is yes, the diagram continues to the third page.

Following the dashed line on the bottom pathway in Figure (3-6), there are two consecutive decision blocks. The first decision block determines whether or not the local community decides to apply to receive funds from a federal government agency through a Pre-Disaster Mitigation grant program (PDM) or a similar grant program, in order to add a flood protection measure to the community. If the answer is “yes” we move to the second decision block which establishes whether or not the application gets approved by the government and the community receives the grant. The PDM grant program is an annual program with limited resources. Every year different communities that are located in hazardous areas compete over this grant. If the community decides not to apply for the PDM grant, or the application does not get approved, the activity diagram comes to an end, meaning that the vulnerability of the community towards future flood damage will not change.

If the grant application gets approved however, the bottom pathway of the diagram continues horizontally to the next action block shaded in grey, which is the design of the flood protection measure. At this stage of the activity diagram, engineers and planners help the community with the design of several structural or non-structural options for flood protection measures. The various design options consider the needs and budget of the community, as well as the physical characteristics of the community site (e.g. shore type, topography, etc.). While each of these design measures offers a certain level of protection, they also have limitations. Some may be socially less desirable for various reasons, for instance removal of a sandy beach or blocking a scenic view of the ocean are not socially desirable. Between different designs for a flood protection measure, the community needs to choose one final option to be implemented. This final option must offer the desired level of protection (e.g., protection against the 100-, or 500- year flood event), be feasible, socially desirable, and most importantly, be cost effective.

Sometimes there are two or more options with similar cost that offer similar levels of protection. The differences could include location, type, or some other feature. Where there are multiple feasible options, the community residents normally get to vote for their preferred option. Thus, next in the activity diagram shown in Figure (3-6) is a decision block, which asks whether there are two or more similar design measure options available. If the answer is "No," the community selects the best option, which is normally the most cost effective one, and it gets implemented. If the answer is "yes," then the next action block will be "Vote" – when the community residents get to vote for their desired option.

Typically, the local government holds meetings with the residents, generally through outreach programs and open house meetings, to educate them about the community flood risks, and the potential flood protection options. After this outreach, the residents vote for their preferred option. The outcome of the vote establishes which measures to implement. This is shown in the upper blocks in the diagram, which transfers the community from an "indecisive" state to a "decided" state.

Following the dashed arrows to the right, after the two pathways merge, comes the "upgrade" box in grey. This action block refers to an upgraded property, whether an upgraded house or an upgrade of the entire community after adding the flood protection measure, which causes a change of state of the property from the state of "at high risk" to the new state of "at low risk" as illustrated in the upper blocks in the activity diagram in Figure (3-6). For the top pathway of the activity diagram, this means there is an upgrade in the house condition (e.g. elevating, flood-proofing, or retrofitting of the house), and for the bottom pathway, the "upgrade" box means that the flood control measures is in place, (e.g. the addition of any structural measure); and as a result, the community moves from a state of "at high risk" to the new state of "at low risk." If the community participates in the community rating system program (CRS) and takes mitigation actions, those actions are classified as a non-structural flood control measure in this model and are included in the "upgrade" action block.

The last action block in this activity diagram before reaching the end point is the "update of risk maps" block. This could be a result of one of the two following cases:

(A) The Digital Flood Insurance Rate Maps (DFIRMs) get updated to include the latest changes in the community flood zones caused by (a) adding any recent flood protection measures, or (b) any upgrade in the individual properties. In this case, the property is assigned to a flood zone with less flood risk.

(B) The community participates in the CRS program and takes mitigation actions towards a higher degree of resiliency for the entire community. This action may not necessarily change the flood zones and an update of the DFIRMs; nevertheless, it will potentially change the flood insurance premiums through the CRS program and thus is classified here as an update in the "Risk map" agent.

Both of the actions mentioned above (A and B) reduce the residents' flood risk, and therefore, their flood insurance premium rates. In the activity diagram shown in Figure (3-6), this is captured in the upper blocks where the state of the insurance premiums changes from "High" to "Low."

This concludes the series of actions leading to a more resilient community. It should be noted that the procedure of "Upgrade" and "Update of Risk maps," on the last page of the activity diagram also occur after the last box on the top pathway at the end of "one single flood event," when a repetitive loss property (RL) gets upgraded to the 100-year flood protection level.

3.3.2.2 Block Definition Diagram for Long-term Event

The block definition diagram (class diagram) for the long-term event is illustrated in Figure (3-7). This diagram is very similar to the class diagram for the short-term event with minor differences in the roles and properties of some of the agents as stated below.

<u>Owner</u>

In the long-term scenario, in addition to the verbs mentioned in the short-term event, the "Owner" agent may decide to upgrade the "Property" and apply for reduced insurance premium rates by submitting a letter of map revision (LOMR) or conditional letter of map revision (CLOMR) to a "Repair fund" agent-NFIP in this case. For the simplicity of our model, we model both application types as one (LOMR). "Homeowners" may upgrade their properties by elevating, flood-proofing, or retrofitting. "Local communities" may add a flood control measure to the community to upgrade it and make it more flood resilient.

Verbs: Upgrade (the "Property"), submit LOMR (to the "Repair fund" agent)

The "Upgrade" method is a complex verb which includes three of the action blocks represented earlier in the activity diagram in Figure (3-6). These three blocks are: "Design," "Vote," and "Upgrade" action blocks.

Repair Fund

This agent, in addition to its short-term roles mentioned earlier in the Figure (3-4) description, takes the role of updating the "Risk map" agent after the upgrade of the "Property" agent. This occurs after the "Owner" requests an update in the flood maps via a LOMR or when a community participates in the community rating system program (CRS) and takes action towards having a more resilient community. The main goal of modifying the "Risk map" agent is to modify the insurance premium rates according to the level of resiliency of the "Property" agent.

Verbs: Modifies the map ("Risk map" agent) after an upgrade of the "Property"

Risk Map

As mentioned earlier, this agent shows the risk of flooding of each "Property" and helps the "Repair fund" agent to set the appropriate fees for the "Owner." The "Risk Map" agent may represent the digital flood insurance rate maps (DFIRMs) or be a criteria for defining reduced premiums for upgraded "Properties" depending on the level of upgrade. When an "Owner" upgrades the "Property" due to an increase in the resiliency of the "Property" they can request a reduction in their flood insurance premiums by submitting a LOMR. Another way that a community's residents can receive premium reductions is if the community participates in the CRS program, which does not necessarily involve a flood risk map revision. In other words, the mitigation actions taken by the local community under the CRS program, although increasing the general resiliency of the community setting, may not be great enough to change the "Property" flood zones to the next lower risk flood zone. The community rating system program (CRS) is described further in chapter 4.

Properties: Community upgrade maps

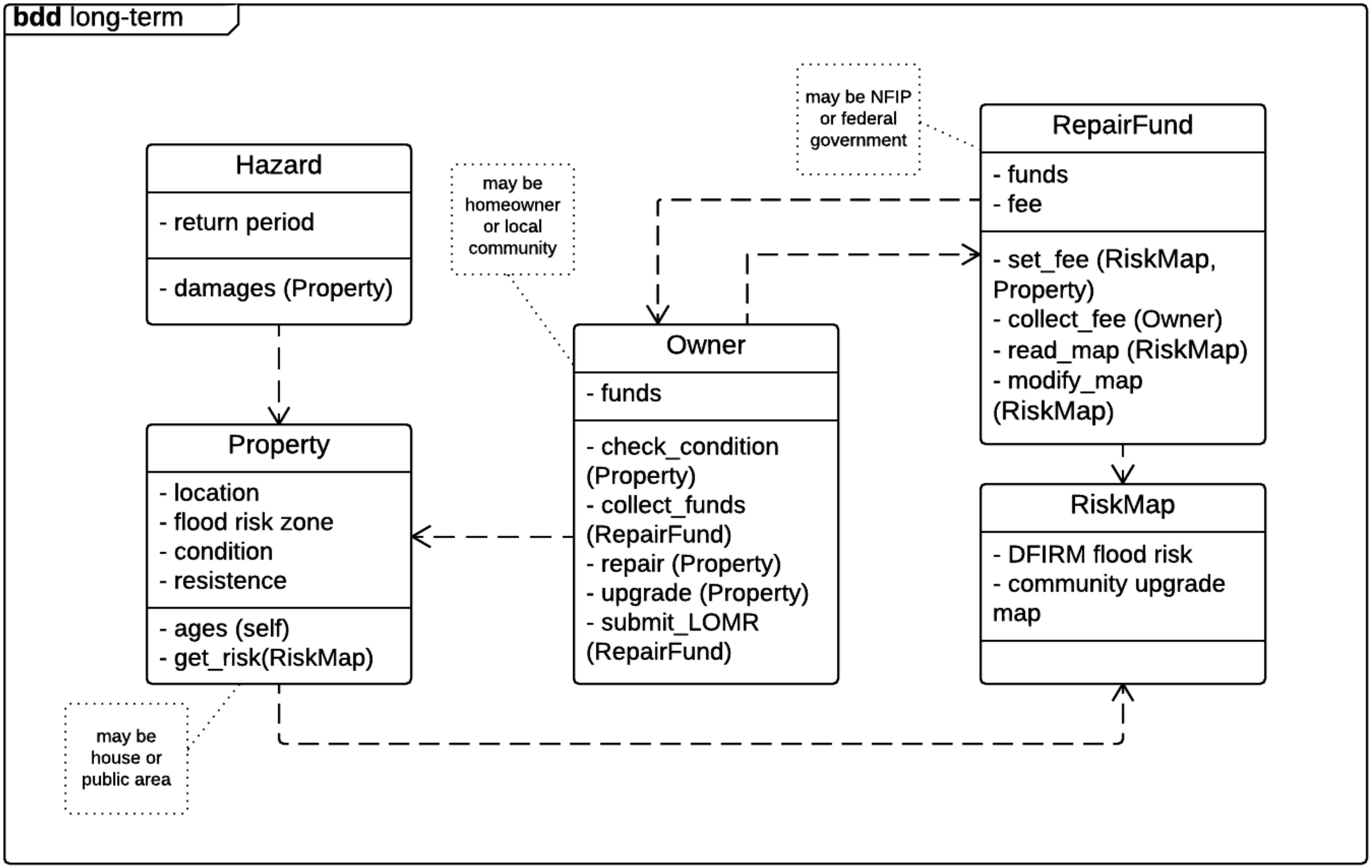

Fig. (3-7): Block definition diagrams of repeated storm events on a community.

3.3.2.3 State Diagrams for Long-term Event

Figure (3-8) demonstrates different states that each class may have in the case of repeated storm events. Some of these diagrams are similar to the state diagrams for short-term events shown in Figure (3-5).

<u>Private property (House)</u>

As mentioned in the description of the state diagram for the short-term event (Figure 3-5), a house may be either in the "undamaged" state before the flood occurs or "damaged" after being flooded. It may remain in the "undamaged" state after a flood event. If the house gets damaged during a flood event, it may move back to the "undamaged" state by getting repaired by the homeowner. If the owner decides to upgrade the house (elevate, flood-proof, or retrofit), the house will move to the "upgraded" state.

<u>Community site</u>

A community site located in a special flood hazard area (SFHA) is "at high risk" of flooding. This state can change to the "resilient" state by adding flood control measures to the community site and/or by upgrading the individual houses in the community. It should be noted that "resilient" is a relative term. Coastal communities are always subject to flooding depending on the severity of the storm events.

Local community

Local communities may be in many different states, two of which are of importance to us in our model: (1) the state of being "indecisive" about which one of the designed flood protection measures to implement to make the community more resilient and (2) the state of being "decided" after the community residents cast their votes and a final option is chosen. This, of course, assumes that the community decides to apply for, and wins the pre-disaster mitigation grant (PDM), and there are several similar options for the proposed flood control measures amongst those designed by the engineers and planners.

Public areas/infrastructure

Similar to houses, public areas may be in the "undamaged" state before the flood happens, move to the "damaged" state after a flood event, and move back to the "undamaged" state after being repaired by the local community. Alternatively, they may stay in the "undamaged" state after a flood event if the storm is not too strong.

Risk Map

The "Risk Map" agent can be in the state of "current" or "effective," which are flood maps that are in effect before an upgrade in the property, or in the state of getting updated after an upgrade. In this study, we have addressed these two states as the "old Risk Maps" and "new Risk Maps," respectively. Noticeably, this could mean the update of the effective digital flood insurance rate maps (DFIRMs) when the upgrade is sufficiently protective to change the flood zone of the property (whether individual private properties or the entire community), or a change in the state of the "community upgrade map" which does not lead to a change in the flood zone, but is sufficient to receive discounted rates on flood insurance premiums for the community residents through the community rating system program (CRS).

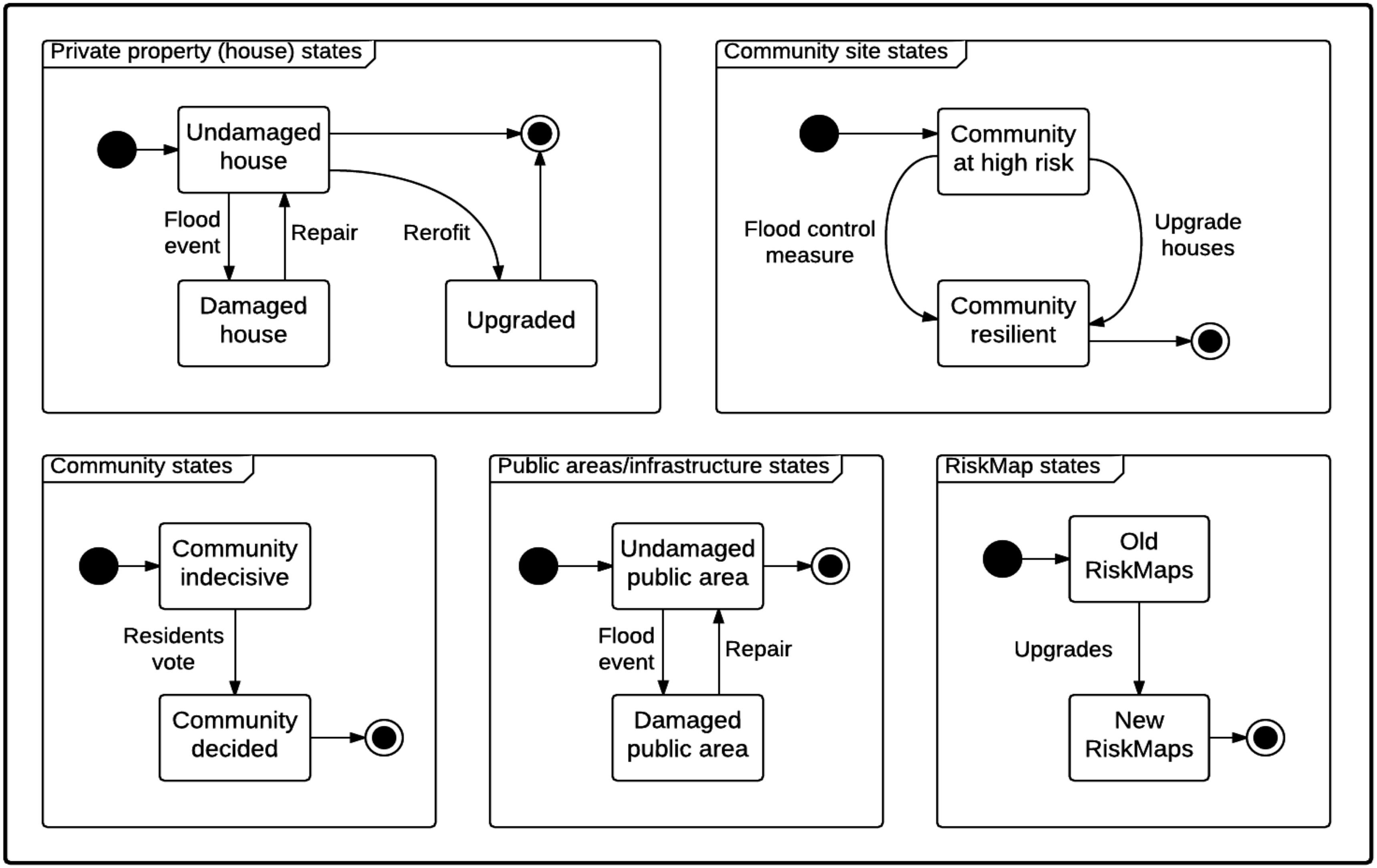

Fig. (3-8): State diagrams of repeated storm events on a community.

3.4 Flood Control Measures

Coastal flood control measures are employed to protect the coasts from flooding by reducing the flood risk, and increasing coastal resiliency. These measures are generally divided into three different categories: structural measures, non-structural measures, and natural and nature-based features (NNBF). Each type of measure is appropriate for a specific shore type, site location, and specific application. Each one of these measures provides a degree of protection and risk reduction through reduction of flooding, waves, or coastal erosion. A combination of these measure types may be used to enhance coastal resilience over the long-term and improve robustness of the coastal flood protection plan.

3.4.1 Structural Measures

Some of the most common structural measures are listed below. A number of these measures are a combination of structural and NNBF types as indicated in parenthesis.

(a) Deployable floodwall

(b) Floodwalls and levees

(c) Shoreline stabilization (seawalls, revetments, bulkheads)

(d) Storm surge barriers

(e) Barrier Island preservation and beach restoration (beach fill, dune creation) (Structural/NNBF)

(f) Beach restoration and breakwaters (Structural/NNBF)

(g) Beach restoration and groins (Structural/NNBF)

(h) Drainage improvements (e.g., channel restoration, water storage/retention features) (Structural/NNBF)

(i) Living shorelines (Structural/NNBF)

3.4.2 Non-structural Measures

The list below includes some of the most common non-structural measures.

(a) Acquisition (building removal) and relocation

(b) Building retrofit (e.g., flood-proofing, elevating structures, relocating structures, ringwalls)

(c) Enhanced flood warning and evacuation planning (early warning systems, emergency response systems, emergency access routes)

(d) Land use management/conservation and preservation of undeveloped land, zoning and flood insurance

(e) Community rating system program (CRS)*

* In this study, we have categorized the community rating systems program (CRS) as a non-structural flood control measure.

3.4.3 Natural and Nature-Based Features (NNBF)

Some of most common NNBFs are listed below. Additional NNBFs are listed under Structural measures.

(a) Overwash fans (e.g., back bay tidal flats/fans)

(b) Reefs

(c) Submerged aquatic vegetation

(d) Wetlands

3.4.4 Measure Applicability by Shoreline Type

The NACCS study conducted by USACE in 2015, has categorized measures based on the shoreline type in their Planning Analyses report. This classification provides an engineering judgment on identifying which type of measure is best suited in a given geographic location, considering the application and limitations of that type of measure. [USACE 2015]. Table (3-1) shows this measure classification and is adopted from the Planning Analyses report of the NACCS study.

Table (3-1): Structural and NNBF measure applicability by shoreline type [Adopted from the Planning Analyses report of the NACCS study. USACE 2015].

Measures	Rocky shores (Exposed)	Rocky shores (Sheltered)	Beaches (Exposed)	Manmade structure (Exposed)	Manmade structure (Sheltered)	Scarps (Exposed)	Scarps (Sheltered)	Vegetated low banks (Exposed)	Vegetated low banks (Sheltered)	Wetlands/Marshes/Swamps (Sheltered)
Structural										
Storm surge barrier[1]			x							
Barrier Island Preservation and Beach Restoration (beach fill, dune creation)[2]			x							
Beach Restoration and Breakwaters[2]			x							
Beach Restoration and Groins[2]										
Shoreline stabilization						x	x	x		
Deployable Floodwalls					x					
Floodwalls and Levees		x			x			x		
Drainage Improvements	x	x	x	X	x	x	x	x	x	x
Natural and Nature-Based Features (NNBF)										
Living shoreline						x	x	x		x
Wetlands							x			x
Reefs	x	x				x				x
Submerged Aquatic Vegetation[3]										x
Overwash Fans[4]										
Drainage Improvements	x	x	x	X	x	x	x	x	x	x

[1] The applicability of storm surge barriers cannot be determined based on shoreline type. It depends on other factors such as coastal geography.
[2] Beaches and dunes are also considered NNBF.
[3] Submerged aquatic vegetation is not associated with any particular shoreline type. It is initially assumed to apply to wetland shorelines.
[4] Overwash fans may apply to the back side of barrier islands, which are not explicitly identified in the NOAA Environmental Sensitivity Index Shoreline Classification dataset.

3.5 Conclusion

This completes the introduction of the systems model for storm damage and community response scenarios. In the next chapter it is shown how the model can be developed into a conceptual agent-based model (ABM) to simulate coastal flood hazard mitigation plans.

Chapter 4

Conceptual Agent-Based Model for Coastal Flood Hazard Mitigation Plans

4.1 Objective

In the previous chapter we introduced a systems model for coastal flood hazard and community response scenarios. The model introduced different agents and decision makers that play a role in the system, their individual properties, the interactions among those agents, and the sequence of actions. In this chapter we develop a conceptual agent-based model (ABM) to simulate the scenarios discussed in the previous chapter. This model will clarify how the system works by quantifying the concepts discussed in the conceptual model. In the following chapters a subset of the ABM constructs will be used to develop a simple, but theoretically informative computational model.

As defined in the systems model, there are multiple stakeholders interacting with each other and with their environment. Each one of them makes decisions individually and independently from other agents. However, all these agents interact with each other and each is affected by its own decisions, as well as the decisions made by other agents. Agent-based modeling is a powerful tool that provides analysts with an understanding of how multiple components of a system are affected by interactions with other components. For instance, the outcome of this model can help homeowners decide whether it is more financially beneficial for them to upgrade their house, or move to a new location that is out of the special flood hazard area (SFHA). On the other hand, local communities may benefit from this ABM model in order to decide how to make their community more resilient against coastal flooding. At the same time, this model can provide insurers with valuable information that helps them find more financially sensible ways to offer insurance plans to homeowners; for example, they can encourage homeowners to retrofit their houses or move to a lower risk flood zone area by offering subsidized flood insurance premium rates or other incentives to those homeowners who do so.

The ABM model also shows the flow of funds in the system between different agents which may help government agencies better understand the potential loopholes in the current system and find ways to better plan for the distribution of funds and future investments.

4.2 Agent-Centric Perspectives

Here we show how each agent (a) views the rest of the system and (b) makes decisions. These characteristics and relations were presented earlier in the class diagrams of the conceptual model introduced in Chapter 3 (Figures 3-4 and 3-7).

It is of particular importance that some agents may represent different components of the system at different stages of the evolution of the system. For example, the "Property" agent may be a "house" or a "public area;" and, depending on the definition of the "Property" agent, the "Owner" agent may be a "homeowner" or the "local community," respectively; similarly, the "Repair fund" agent may represent the national flood insurance program (NFIP) or the federal government, respectively. This is because, as illustrated in the activity diagrams in the previous chapter (see Figures 3-1 to 3-3, and 3-7), there are a series of similar actions taken by different components of the system. For example, when a house gets damaged, the homeowner receives repair funds from the NFIP and repairs the property. Similarly, when a public area gets damaged as a result of a flood event, the local community, which is responsible for the public areas, applies to get repair funds in the form of hazard mitigation grants from federal government. Both of these series of actions follow the pattern shown in Figure (3-1). A property gets damaged, then the agent responsible for that property obtains repair funds from the appropriate organization and repairs the property. It is common in computer programming to write the code as briefly as possible and shorten the length of the code and the number of commands as much as possible to increase efficiency and reduce the run time of the code. This is often done by introducing loops to perform repetitive actions. In our model, we have applied this general coding rule by giving multiple interchangeable roles to some of the agents. More description is provided below for each of the agents.

4.2.1 Property

Property may refer to a "house" or a "public area." This agent is not considered a stakeholder of the model as it does not make any decisions. However, depending on the type of the property, the role of other agents will be defined, e.g., if the "Property" is a "house," the "Owner" agent will be the "homeowner;" when "Property" refers to a "public area," the "Owner" agent is the "local community" in charge of the public areas.

4.2.2 Owner

This agent may represent the "homeowner" where the "Property" agent is a "house," or the "local community" where the "Property" agent is a "public area." The characteristics listed below are common to both homeowners and local communities. The homeowners and local communities each also have their own specific properties that are listed later under their own names. Here is a list of how this agent (a) views the rest of the system and (b) makes decisions.

(a.1) Has knowledge of the state of the property. This knowledge is defined as a variable in the model and must be updated after each storm and each repair.

(a.2) Is responsible for the property, i.e., after the property is damaged by a flood event, the owner is responsible for repairing the property.

(a.3) Has knowledge about the repair fund annual fees and repair fund payments if the property is damaged. These are also defined in the model as variables that are updated regularly.

(a.4) Has some assets or savings which we call “funds” in our model. These funds will fluctuate as a result of actions that the owner takes, i.e., paying repair fund fees decreases these funds and collecting repair funds from the “Repair fund” agent will increase these funds.

(b.1) Every year, decides whether or not to pay repair fund fees.

As mentioned earlier, the “Owner” could be a “homeowner” or the “local community.” If the “Owner” is a “homeowner,” every year they will decide to either pay repair fund fees (in the form of flood insurance premiums) or to not purchase flood insurance. It should be noted that “not having flood insurance coverage” is only an option in case that there is no mortgage or loan on the house located in the special flood hazard area (SFHA). If a property is located in the SFHA, lending institutes are required by federal law to make flood insurance coverage a condition for the loan. The “homeowners” who decide to purchase flood insurance pay flood insurance premiums to the National Flood Insurance Program (NFIP). Noticeably, when the “Owner” agent is a “homeowner,” and the fees refer to flood insurance premiums, the “Repair fund” agent in the model appears as the NFIP. However, “homeowners” also pay taxes to the government in which case the “Repair fund” agent of the model would be the “local and federal government.”

On the other hand, if the "Owner" agent is a "local community," then the "Repair fund" agent would be the "federal government" and the payments would be in the form of federal taxes. Of course in this case, the "Owner" has no choice but to pay the tax to the government.

(b.2) After flood damage, decides to ***repair*** the property, or ***repair and upgrade*** the property to be more resilient towards future flood events. The latter would be an investment that will cost the owner in the short run. In the long run, it helps the owner save money by reducing the risk of flooding in the future which would lower flood insurance premium rates.

To be more specific, we explain here what "upgrading" means for each type of "Owner." If the "Owner" is a "homeowner", they can retrofit, flood-proof, or elevate the house to reduce their exposure to flood risk. Then they can request a lower flood insurance rate from the NFIP by submitting a letter of map revision (LOMR) and providing technical evidence that their house has a lower risk of damage after the upgrade.

Conversely, if the "Owner" is a "local community," they can make the community setting more resilient by adding structural or non-structural flood protection measures. Similar to the case of homeowners, the community can also request an update of the flood risk maps and lower the rate of insurance premiums for its residents through a letter of map revision (LOMR), conditional letter of map revision (CLOMR), or by participating in the community rating system (CRS), which is a voluntary program for NFIP-participating communities. The NFIP uses the CRS to figure out the insurance discounts, and they give special attention to communities that, on their own, try to go beyond NFIP minimum criteria for protection from flood events or in increasing the number of flood insurance policies [King 2005].

4.2.3 Owner (homeowner)

When the "Owner" agent represents a "homeowner," it has the following characteristics listed below that are specific to the "homeowner" and, unlike the previous list, are not shared between the "homeowner" and the "local community" agents.

(b.3) After flood damage, decides to ***relocate*** and move to a new location with smaller flood risk, or ***stay*** in the same location and repair the damaged house.

(b.4) If the homeowner decides to stay and repair the damaged house, and if the house has flood insurance coverage, then the homeowner submits an insurance claim and ***collects repair funds*** from the insurer who is defined as the "***Repair fund***" in the model. As mentioned in the previous chapter, after flood damage, repetitive loss properties (RL) which are prone to repeated storm damage are required by the NFIP to repair and upgrade to a minimum of 100-year flood event resistance. This is referenced as "repair and upgrade" in the activity diagrams in the previous chapter (See Figure 3-6).

(b.5) ***Pays tax***. Every year, homeowners pay tax to the federal and local government, which is one of the main sources of the government's income. This act is classified as "collect fee" by the "Repair fund" agent in the class diagram in Chapter 3 (see Figures 3-4 and 3-7).

4.2.4 Repair fund

This agent may represent the "NFIP," or the "federal government" if the "owner" agent is a "homeowner" or the "local community," respectively. Regardless, it has the following characteristics.

(a.5) Has funds, which will increase by collecting fees from the "Owner" or decrease when the "Owner" agent, whether it is the homeowner or the local community, "collects funds" to repair damaged properties after a flood event.

"NFIP" pays repair funds to the homeowners through insurance claims and the "federal government" normally provides local communities with repair funds through the Hazard Mitigation Grant Program (HMGP).

It should be noted that there are several other grant programs offered by different government organizations that provide "repair funds" to the "Owners," including homeowners and local communities; in this study, to save time and for the sake of simplicity of our model, we only consider the programs mentioned above. It would be straightforward, yet time-consuming, to revise the model to include other existing grant programs. This can be done as future work by interested researchers.

(b.6) ***Sets the fees***. The "Repair fund" agent is responsible for setting the rates of fees and payments for the 'Owner" agent.

When the "Repair fund" agent is the federal government, it sets the tax rates for the communities as well as individuals (i.e., homeowners or renters).

However, when the “Repair fund” agent is the NFIP, it defines the flood insurance rates for the “homeowners” by means of the digital flood insurance rate maps (DFIRMs) which divide the community setting into different flood zones and show the risk of flooding for each flood zone. The rate of flood insurance premiums for each property is defined based on the flood zone in which the property is located. This act is referred to as “read map” and the DFIRMs are categorized under the “Flood risk” agent in our model as shown in the class diagrams (Figures 3-4 and 3-7) of Chapter 3. These insurance premium rates can be adjusted if a homeowner decides to upgrade the property by elevating or flood-proofing. Likewise, when a community implements a flood control measure, the insurance rates of the residents will change due to the change in flood zones and the update of the DFIRMs after the measure is in place. Another way that a community may decrease the flood insurance rates for its residents is through participating in a community rating system program (CRS), as mentioned earlier.

(b.7) ***Collects the fees***. After the “Repair fund” sets the fee rates, this agent then collects the fees from the “Owner” agents. “NFIP” collects fees in the form of insurance premiums from the “homeowners;” the “federal government” collects fees in the form of tax from “homeowners /residents” and “local communities.”

4.2.5 Repair Fund (NFIP)

The characteristics listed above are shared by both the "NFIP" and the "federal government." Here we describe some actions that are specific to the "NFIP" only.

(b.8) ***Reads maps***. As mentioned in (b.6), the "NFIP" sets flood insurance premium rates for each resident based on the flood zone in which their property is located. Flood zones are delineated in digital flood insurance rate maps (DFIRMs) that show the risk of flooding for the community location.

(b.9) ***Modifies the maps***. If a homeowner or community upgrades its property through one of the methods described earlier (e.g., elevating, flood-proofing, or adding a flood control measure) such that it decreases the risk of flooding of the property enough so that it is reassigned to a different flood zone, then a letter of map revision (LOMR), accompanied with appropriate technical evidence, may be submitted to NFIP. Upon the acceptance of the map revision request, the DFIRMs get updated to show the referred properties in the correct flood zone. This will automatically decrease the flood insurance premium rates for those homeowners.

4.2.6 Risk Map

This agent may represent "DFIRMs" or the "community upgrade maps" in our model. As mentioned in (b.6) and (b.8), DFIRMs define the flood zones in a community map and are used to define the flood insurance premium rates for each property. They may get updated if the "Property" agent gets upgraded.

The “Community upgrade map” agent in our model refers to the case when the flood insurance premium rates change as a result of the community participating in the community rating system (CRS) program. As mentioned earlier, this program offers lower insurance rates to the residents of the participating communities when they go above and beyond the minimum required NFIP standards to protect their community against flooding. In this case, although the flood zones may not change and the DFRIMs do not necessarily get updated, the insurance premiums change according to the CRS principles.

Since both “Community upgrade map” and the “DFIRMs” are used to define flood insurance premium rates for the residents of a community, we categorized them together in one group as the “Risk map” agent.

4.3 ABM Controller Parameters

As mentioned earlier, our primary goal in developing an ABM is to understand the interactions between the players of the system and their mutual impacts on one another. One way in which this goal can be achieved is by changing model inputs and studying the model results after each input modification. In the section we introduce a number of controller parameters that could be used in a computational form of this ABM. These variables allow the user to define the input to the model and investigate the influence of each one of the system components by studying the model results after changing each one of the parameters indicated below.

4.3.1 Storm Intensity

This parameter is used to vary the intensity of the storm in the ABM. The storm intensity is associated with a return period and a probability of occurrence as noted earlier. In equation (4-1), we show the standard binomial distribution result of the probability P_e of at least one T-year storm happening during a period of n years, where T is the return period of the storm. For instance, during the typical 30-year length of a mortgage, there is 26.03% chance of at least one 100-year storm event occurring.

$$P_e = 1-[1-(1/T)]^n \qquad (4\text{-}1)$$

The intensity for a T-year storm is determined by the geographic location of the property and is quantified by flood level maps. Here are the consequences of increasing the intensity of the storm:

Short-term effects:

(a) The probability of damage for each property increases.

(b) The size of the flood risk region increases.

(c) There will be more owners with damaged houses.

(d) There will be more owners with severely damaged houses.

(e) The “Repair fund” agent will need to pay more claims.

Long-term effects:

(a) The “Repair fund” agent may increase its fees.

(b) More owners may decide to upgrade their properties.

(c) More owners may decide to sell their properties and relocate.

(d) The community may decide to add a flood control measure.

(e) The community may decide to encourage its residents to upgrade their homes and to participate in the community rating system (CRS).

4.3.2 Insurance fees

This is related to the annual cost of flood insurance for each homeowner. In our model, we set the initial value to be 1.0 so that, for example, if this is set to 1.1 in any future year, then the cost will increase by 10%. Here are the consequences of increasing this parameter above 1:

Short-term effects:

(a) The homeowner may decide not to purchase flood insurance (in case there is no loan on their property).

Long-term effects:

(a) The homeowners may not be able to afford an upgrade due to an increase in their total annual costs (higher insurance fees).
(b) The homeowner may decide to upgrade to obtain a discount on their insurance fee.
(c) The homeowner may decide to move and relocate.

4.3.3 Insurance Discount

The NFIP uses the community rating system (CRS) to figure out discounts to communities that go beyond NFIP minimum standards. These communities earn points based on their hazard mitigation actions, with more points leading to more discounts. These communities use their number of their points to apply for different levels of ratings. These ratings range from Class 1 (highest number of possible points; 45% premium reduction) to Class 10 (no points; 0% premium reduction).

Previously, we described the CRS as a non-structural measure that local communities may use to improve their overall coastal resiliency. The community can also apply for a flood control measure; furthermore, such a measure and the CRS can be added to the system simultaneously, to increase resilience as well as the insurance discount. Here are the consequences of increasing the discount:

Short-term effects:

(a) The community may decide to set some regulations (e.g., mandatory upgrade of the private properties to some level of flood-resistance) to become eligible for the premium discount.
(b) There will be an increase in the homeowners' costs (for upgrades).
(c) There will be a decrease in NFIP income due to reduced flood insurance premium rates.

Long-term effects:

(a) The homeowner's average cost of flood insurance will decrease after an upgrade.

(b) The homeowner's total cost of repair + insurance will decrease due reduced risk of flood damage to their house after the upgrade.

(c) The average and total costs of NFIP will decrease as a result of an increase in the number of more resilient properties and fewer insurance claims.

4.3.4 Pre-disaster Mitigating Grant (PDM)

Pre-disaster mitigating grants are provided by the government every year to assist local communities in upgrading their community settings and becoming more resilient. Local communities submit their grant application along with their local mitigation plan proposal to receive this grant. Since this budget is limited, many community applications get rejected every year. The communities who receive the grant will need to contribute in part from their own funds to the cost of building the proposed flood control measures. Greater availability of funds can lead to the building of stronger measures, which provides more protection and decreases the amount of loss. Increasing the amount of the PDM grant by the government may motivate more communities to apply for the grant and enables them to make better mitigation plans. A parameter for this grant can be introduced to investigate how this grant may affect the community behavior. The grant funds are typically covered by the taxes collected from the homeowners of the community; therefore, an increase in the grant amount requires an increase in tax rates.

Short-term effects:

(a) The communities may be more encouraged to apply for the grant.

(b) Stronger measures may be constructed leading to more resilient communities.

(c) There will be a short-term increase in the costs of the local communities for partially participating in the costs of the measure construction.

(d) There will be an increase in the costs to the federal government as a result of offering more grant funds to the communities.

(e) The homeowners may not be able to afford an upgrade of their own residence due to an increase in their annual costs (due to the associated rise in taxes).

Long-term effects:

(a) The number of HMGP requests will decrease as a result of more resilient coasts and less flood damage to public areas.

(b) Flood damage will be reduced due to communities being more flood-resistant.

4.3.5 Flood Control Measure

As mentioned in the previous chapter, there are many different types of flood control measures available. Engineers and planners decide on appropriate types of measure for each community based on several characteristics of the community site, e.g., shore type, slope, topography and bathymetry of the coast, beach size, etc. Here, for the sake of simplicity, we introduce a few representative options for the measure variable:

(A) No measure

(B) Floodwalls

(C) Beach restoration

(D) Breakwaters and Groins

A more complete list of possible options for the measure is provided in Table (3-1) of Chapter 3. The measure parameter can also include an option to control the strength of the measure, total cost of building and maintenance of the measure, and the level of protection offered by the measure (e.g., protection against 100-, 200-, or 500-year flood).

4.3.6 Homeowner upgrade strategy

It may be useful to introduce a parameter that quantifies the level of homeowner behavior in response to insurance premium reductions offered by NFIP to homeowners who upgrade their property. Basically, this parameter would be related to the probability that a homeowner will upgrade as a function of the insurance discount – for instance, if the insurance discount is 10%, then the probability that the homeowner will upgrade is 20% if the parameter is set to 2, and the probability of upgrade is 30% if the parameter is set to 3.

An alternate approach is to use basic economics concepts to determine the upgrade-related reactions of the homeowner in response to an insurance discount. This approach is followed in the ABM developed in Chapter 5.

4.3.7 Other Possible Controller Parameters

Here are some other controller parameters one can potentially add to the model for future model improvements:

- Parameters of the fragility curves of the buildings that relate the probability of damage with the severity of the flood;

- Availability of homeowner funds (to be used for upgrades);

- Cost, type, and spatial coverage of possible protective measures;

- Local community upgrade strategy (in response to the PDM parameter);

- Propensity of homeowners to move to a different flood zone;

- Propensity of the entire community to move to a less flood-prone location;

- Availability of extra repair funds beyond Federal assistance that might be in the form of a loan or may be outright gifts, and may be at the individual or community level.

4.4 ABM User Needs

Here we explain how an ABM can inform the actors in the system to make better decisions. We present scenarios on how each agent may use the model features to obtain an understanding of their roles, behaviors and consequences.

4.4.1 Homeowner

As described earlier, the homeowner has multiple roles and decision-making responsibilities:

(a) As an ***insurance payer*** the homeowner:

(a.1) Decides to pay or not pay insurance (required only if they are in the 1% flood zone or if they have a loan on their property)

(b) As the ***agent responsible for repair/upgrade of the property***:

(b.1) Decides on the level of repair/upgrade of the property

(b.2) Decides whether to stay or sell and move (relocate)

(c) As a ***community representative***:

(c.1) Votes on possible community flood control measures

The ABM can help inform these decisions in the following ways:

(A) Estimates of short-term costs for a single storm event

a. Input: parameters showing decisions on

i. The level of the flood insurance coverage on the property

ii. Last level of repair/upgrade of the property

iii. The severity of the storm event

b. Output:

i. Total costs of: repair + insurance

ii. Level of damage to the house

(B) Estimates of long-term costs for multiple events

a. Input:

i. Upgrade strategy (e.g., after every event, if there is damage, then the house is repaired to 1% flood resistance or the house is repaired to the next higher level of resistance)

ii. Move and relocation strategy (e.g., never move, move after damaged twice, etc.)

iii. Voting on flood control measure options

b. Output:

i. Total cumulative cost over time

ii. Average cost over time

iii. Cost versus severity of event. (Cost for every event, grouped according to severity.)

iv. Effects of each measure option on the property (access to the beach, potential blockage of scenic views, etc.)

4.4.2 Local community

The roles and decision-making responsibilities of the local communities can be summarized as the following:

(a) As an ***NFIP participating community*** the local community:

(a.1) Decides whether or not to participate in the community rating system program (CRS)

(b) As the ***agent responsible for repair/upgrade of the community setting***:

(b.1) Decides on the level of repair/upgrade of the public areas and infrastructure after storm damage; and/or upgrade of the entire community by implementing flood control measures

(b.2) Decides whether or not to apply for the FEMA pre-disaster mitigation grant program (PDM) for implementing a flood control measure

The ABM can help inform local communities in the following ways:

(A) Estimates of short-term costs for a single storm event for the local community.

a. Input:
    i. The severity of the storm event
    ii. Last level of repair/upgrade of the public areas
b. Output:
    i. Total cost of repair
    ii. Level of damage to the public areas

(B) Estimates of long-term costs for multiple events for the community

a. Input:

   i. Repair and upgrade strategy for the public areas (e.g., after every flood damage, repair the public areas to 1% flood resistance or to the next higher level of resistance)

   ii. Flood control measure options (including community participation in the CRS program as a non-structural flood control measure)

b. Output:

   i. Total cumulative cost over time (including the cost of implementing flood control measures, as well as the cost of repair and upgrade of public areas after flood damage)

   ii. Average cost over time

   iii. Cost versus severity of event (cost for every event, grouped according to severity)

   iv. Effects of each measure option on the community (level of protection offered by each measure, change in flood zones and insurance premium rates for the community residents, social effects of the measure, etc.)

4.4.3 Insurer

The insurer needs to keep premiums affordable, but cannot lose money. Their responsibility and decision-making roles are as follows:

(a) ***Control homeowner behavior***

(a.1) Encourage policy holders to upgrade their properties and lower the risk of flood damage and potential number of claims by setting insurance premium rates according to the level of resistance of the homes.

(b) ***Stay solvent***

(b.1) Set rates to offset repair costs.

A computational ABM should combine the influences of the two roles (a) and (b) to help design efficient rates. As the discount on the insurance rate increases, then the ABM should show a greater number of homeowners proceeding with residential upgrades in response to the more attractive discount. This would lead to a decrease in the cost of claims. This relationship between the insurance discount and claims cost is plotted in Figure (4-1) with the x-axis for the discount and the y-axis for the claim cost. If this relationship is concave, and if the total cost for the insurer is linearly increasing with respect to both the discount and claims cost, as indicated by the parallel contour lines in this figure, then there would be a unique value for the discount where the insurer can minimize cost (maximize revenue). This unique value corresponds to the point of tangency indicated in the figure. Clearly there is a trade-off between offering more attractive insurance discounts to induce homeowner to upgrade, versus the loss of revenue associated with this discount. It is this trade-off, quantified by the parallel lines in the figure, along with the homeowner reaction to the discount, quantified by the concave curve that determines the final value for the discount.

The ABM can help inform insurers by investigating different scenarios of homeowner behavior while monitoring cash flows associated with fees, discounts and claims:

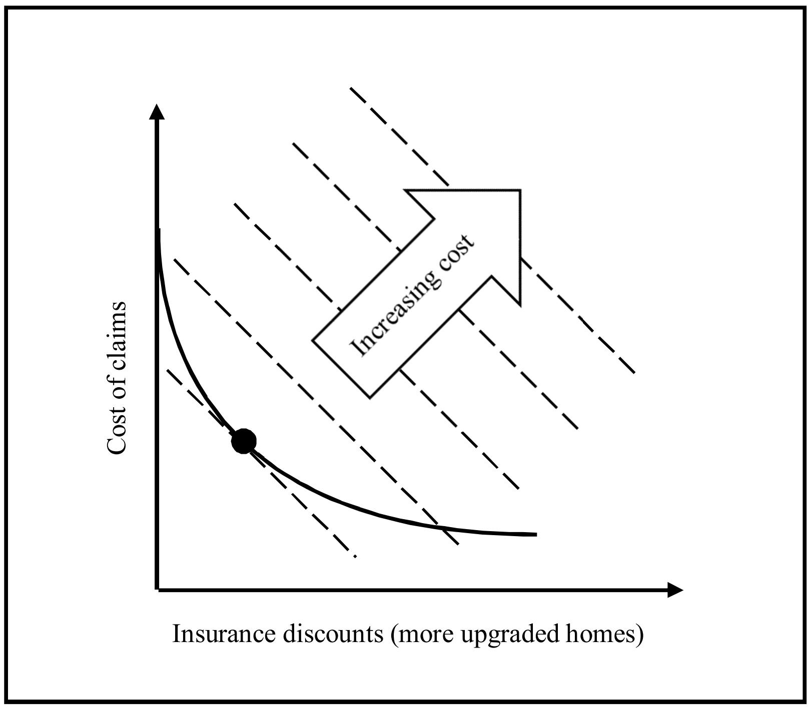

Fig. (4-1): Diagram of the insurer's expected costs with respect to discounts. The diagram implicitly includes homeowners' behavior as described in the main text.

(A) Simulation of the number and degree of residential upgrades

a. Input:

i. Discount parameter (e.g., 10% discount for each higher level of house flood resistance)

ii. Homeowner upgrade strategies (e.g., a parameter showing the probability that a homeowner will upgrade in response to the amount of discount).

b. Output:

i. Average amount of residential upgrades

ii. Total claims, compared with the baseline premiums (no discount)

(B) Solvency calculations

a. Input:

i. Insurance premium rates (baseline)

b. Output:

i. Difference between premiums collected and output claims over a long duration

4.4.4 Federal government

The federal government has similar roles and responsibilities as the "Insurer" agent (NFIP). This means the government needs to keep taxes and fees affordable for the payers; at the same time it can exercise control over the "Owner" agent's behavior by setting the fee and discount rates. It is noted that the federal government has other sources of income and, hence, solvency is not an issue; nevertheless we will assume that it will be a zero-cost, zero-revenue generating entity as we assumed for the insurers. The responsibility and decision-making roles for the federal government are as follows:

(a) ***Control owner behavior***

(a.1) Encourage local communities to upgrade their properties and make their communities more resilient by offering pre-disaster mitigation grant programs (PDM) to help them implement flood control measures. This will decrease the potential number of hazard mitigation grant (HMGP) requests in the future.

(b) ***Stay solvent***

(b.1) Set rates to offset repair costs.

As for the analysis of the roles of the insurer, the computational ABM should show how the influences of the two roles (a) and (b) can be combined to determine cost-efficient rates and the number of pre-disaster mitigation grants (PDM) offered to the communities each year.

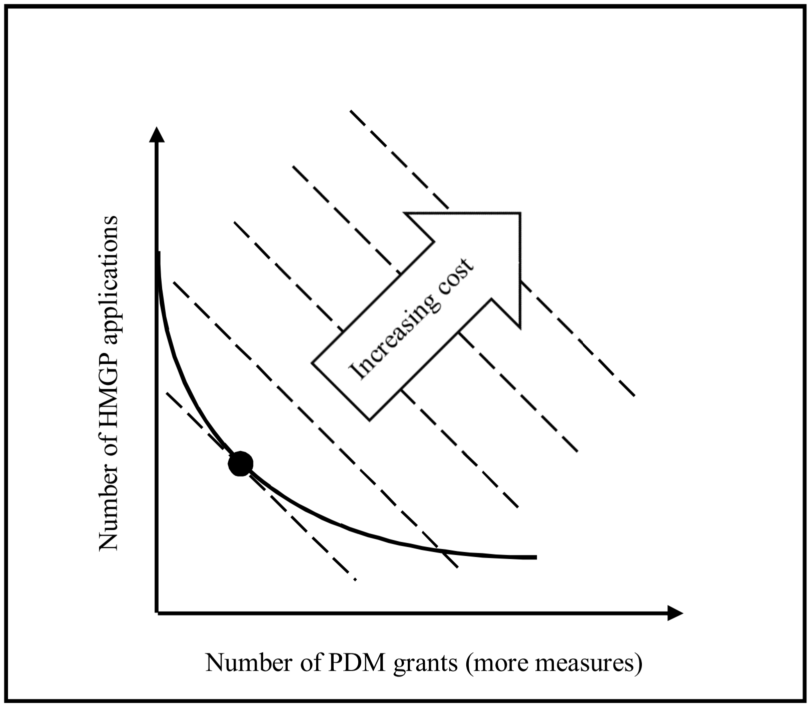

Fig. (4-2): Diagram of the federal government's expected costs with respect to the number of PDM grants. The diagram implicitly includes the behavior of the communities as described in the main text.

Figure (4-2) shows the expected cost diagram for the federal government, which follows the same pattern as the diagram for insurer's costs in Figure (4-1). The x-axis shows the number of pre-disaster mitigation grants (PDM) offered to the communities to build flood control measures and the y-axis shows the number of hazard mitigation grant (HMGP) applications after flood damage. The higher number of PDMs offered to upgraded communities leads to a higher degree of coastal resiliency and fewer HMGP requests for the repair of damaged public areas by local communities, as indicated by the curve in the figure. The parallel lines represent the total cost to the federal government, which is assumed to increase linearly with respect to both HMGPs and PDMs. The optimal number of PDMs corresponds to the point of tangency indicated in the figure.

The ABM can help inform federal policymakers by investigating different scenarios of community behavior while monitoring cash flows and coastal resiliency:

(A) Simulation of the coastal resiliency of communities

a. Input:

i. PDM parameter which governs the number and amount of pre-disaster mitigation grants offered to the local communities each year

ii. Community upgrade strategy (e.g., parameter showing the probability that a community will upgrade as related to the amount of PDM grant – for instance, if there is a 10% increase in the amount or number of PDM grants in (i), then the probability that the local community will upgrade and add a flood control measure is 20%).

b. Output:

i. Average degree of coastal resiliency (number of, and the protection level offered by, the flood control measures).

ii. Total number of HMGP requests (for the repair of damaged areas), compared with the baseline (in which there are no PDMs and therefore no flood control measures)

(B) Solvency

a. Input:

i. Budget allocation for coastal resilience

ii. The number and cost of PDMs offered

b. Output:

i. Difference between budget allocation and output HMGP claims + PDMs offered over a long duration

Chapter 5

Computational Agent-Based Model for Storm-Surge Resilience

5.1 Introduction

The purpose of developing the conceptual agent-based model in Chapters 3 and 4 is to provide the foundation for constructing computational ABMs for storm-surge resilience. As noted in the introduction, it is possible to proceed with two types of ABMs: (1) a highly detailed model that incorporates all of the agent behaviors and interactions and environmental influences that were described in the previous chapters or (2) a simplified model with assumptions that reduce complexity and with behaviors and interactions that are aggregated to limit the number of agent decision rules. While it may appear that the first option would produce the most realistic model, this is arguable because the accuracy of such a model depends highly on data availability. In fact, much of the information needed for agent behaviors, such as those that would inform upgrade, retrofit and relocation decisions are not available. There is a separate data collection effort within the Hazard SEES NSF project to estimate possible behavioral rules; this effort, combined with the conceptual ABM presented in Chapters 3 and 4, will lead to the development of a detailed computational ABM.

A simplified ABM would be useful only if it provided insights that would be difficult to obtain from a highly detailed ABM. These insights should be valuable by themselves, and should also be helpful in future model development.

In this chapter, we explain how the concepts in the previous two chapters can be distilled into a simplified ABM; we then demonstrate the insights that it can provide through a series of graphs and results in this and in the following chapter. The equations that govern agent behavior provide some of this insight, but the most interesting aggregate behavior can be seen through a series of plots that are similar in character as those used in economics. It is shown that some insights are possible even before running the computational model. In Chapter 7, it is shown how the simplified ABM can be integrated into two other models for community resilience, one based on sociology theory and the other based on a high-level system dynamics approach.

The mathematics in this chapter is quite basic: we only need to rely on basic decision theory, using expected values (mean values) to handle uncertainties [Benjamin 2014]. The equations from this theory are used by the agents of the system to determine the best choice from each agent's perspective. Clearly there will be interactions between the agents with each decision of each agent affecting the other agents in the system.

The chapter begins with a set of assumptions and aggregations needed to simplify the conceptual ABM developed in the previous two chapters. Then, the uncertainties associated with storm intensity, structural damage and agent characteristics are described and used as input into the decision theory equations for agent behaviors. The behavior of the insurer is the most complex. While this behavior is determined numerically by minimizing costs, it is shown how this behavior can be explained in terms of a contour plot that maps insurer cost over household behavior. In Chapter 6, a set of example runs is presented to illustrate various possible scenarios of community resilience in the form of infrastructure upgrades and building. It is shown how these scenarios develop in response to the degree of storm surge hazard, infrastructure cost, and other parameters of the system.

5.2 Model Simplifying Assumptions and Aggregations

As noted in the preceding subsection, the first step in building the simplified computational ABM is in setting the assumptions of the system and describing the aggregation of behaviors and interactions of the conceptual ABM. These are described in the following:

1. Storm
   a. Only a few discrete levels of storm intensities are possible.
   b. Each level of storm is modeled as a T-year event using Bernoulli sequence theory.
   c. Each storm subjects all residences with the same hazard risk (i.e., all residences experience the same storm hazard).
2. Residences
   a. Only a few discrete levels of residential damage are possible.
   b. All residential structures have identical:
      i. Cost of repair for each level of damage.
      ii. Cost for upgrade.
      iii. Probabilities of damage for a given storm level intensity, level of damage, upgrade status (upgrade or no upgrade) and community measure status (measure or no measure).

3. Homeowners

    a. All homeowners have identical cost of suffering for each level of damage that is not covered by insurance.

    b. Each homeowner has a different cost of risk (cost of worry):

        i. This cost is zero if the residence is upgraded.

        ii. This cost is included in the decision rule for considering an upgrade.

    c. Each homeowner has a different level of affordability:

        i. Affordability is quantified by a budget allocation for insurance, residential upgrade and tax (if any) for a community measure. It is not related to cost of suffering or cost of risk.

        ii. Homeowners will always pay the insurance and tax, even if the sum is above their budget allocations.

        iii. Homeowners will consider the upgrade only if they can afford it. These homeowners will follow a separate decision rule on the upgrade that is related to expected costs.

4. Insurer

    a. There is only a single insurer that will serve as an aggregated entity that will perform the following services:

        i. Collect the identical insurance fee from all homeowners.

        ii. Pay the complete cost of repairs (i.e., no deductible), but none of the cost of suffering.

iii. Provide the same insurance fee discount to any homeowner who has upgraded their residence.

iv. Collect (on behalf of the community) a tax to pay for a community measure if the homeowners decide to build the measure. This tax is the same for all homeowners and is simply added to the insurance fee.

b. The insurer adjusts the discount and insurance fee in the following manner:

i. The discount rate is set to minimize loss.

ii. The fee is set so that there is no net profit or loss.

5. System timeline

a. The cost of upgrades and the cost of any measure are distributed over a fixed number of years at a constant monetary discount rate.

b. All upgrades and any measure are built at the following time:

i. Time 0 before expected costs are computed.

ii. No further upgrades or measure is considered until after the time period in 5a.

c. The time period in 5a is sufficiently short so that it is not necessary to consider inflation, depreciation, or structural degradation.

While these simplifications are quite broad, it will be shown in the following how a computational ABM that is based on the above exhibits complex behaviors and can provide useful insights into the system characteristics. It is noted that items 3b and 3c give homeowners a distribution of risk aversion and purchasing power behaviors that we will be able to explore in several ways using simple visualization tools. Items 4a and b govern market behavior that results in feedback wherein an individual homeowner's decision on upgrading indirectly affects other homeowners' decisions. Finally, item 2b on the costs of improvements do not produce linear effects on the system due to the reactive adjustments in homeowner decisions on upgrades and insurer decisions on fees and discounts.

5.3 Homeowner's Decision Tree

We begin the development of the computational ABM with the decision tree of the homeowner, which governs most of the behavior of this class of agents. Figure (5-1) shows a decision tree and the pathways and outcomes associated with the various possible decisions and states [Clemen 2000]. In this case, the decision is to upgrade or not upgrade the homeowner's property. Once this decision is made, there are two states to consider: the possibility of a storm and the possibility of damage due to the storm. According to assumptions 5a and b, the decision is only made once at the beginning of an X-year interval with cost evenly distributed over every year of this time interval. According to assumption 5c, we do not have to consider variations in costs due to inflation or depreciation or variations in the residential structural strength due to degradation. Taken together, this implies that we can perform the analysis of the decision tree by considering only a single year during the X-year interval. Finally, with assumption 1b on the Bernoulli sequence property of storms, we only need to consider either zero or one storm during this single year. Assumption 1a indicates that several types of storms are possible. We only consider one level of storm intensity in the diagram; it is straightforward to extend this to multiple levels, and this is done in by inserting summations in the equations associated with this decision tree.

With assumption 1c, we can consider all houses of the community to be located in a single flood zone, sharing the same risk of flooding. We assumption 2b, we can consider all houses to be at the same level of flood resiliency, meaning they all have the same risk of damage for a given storm intensity.

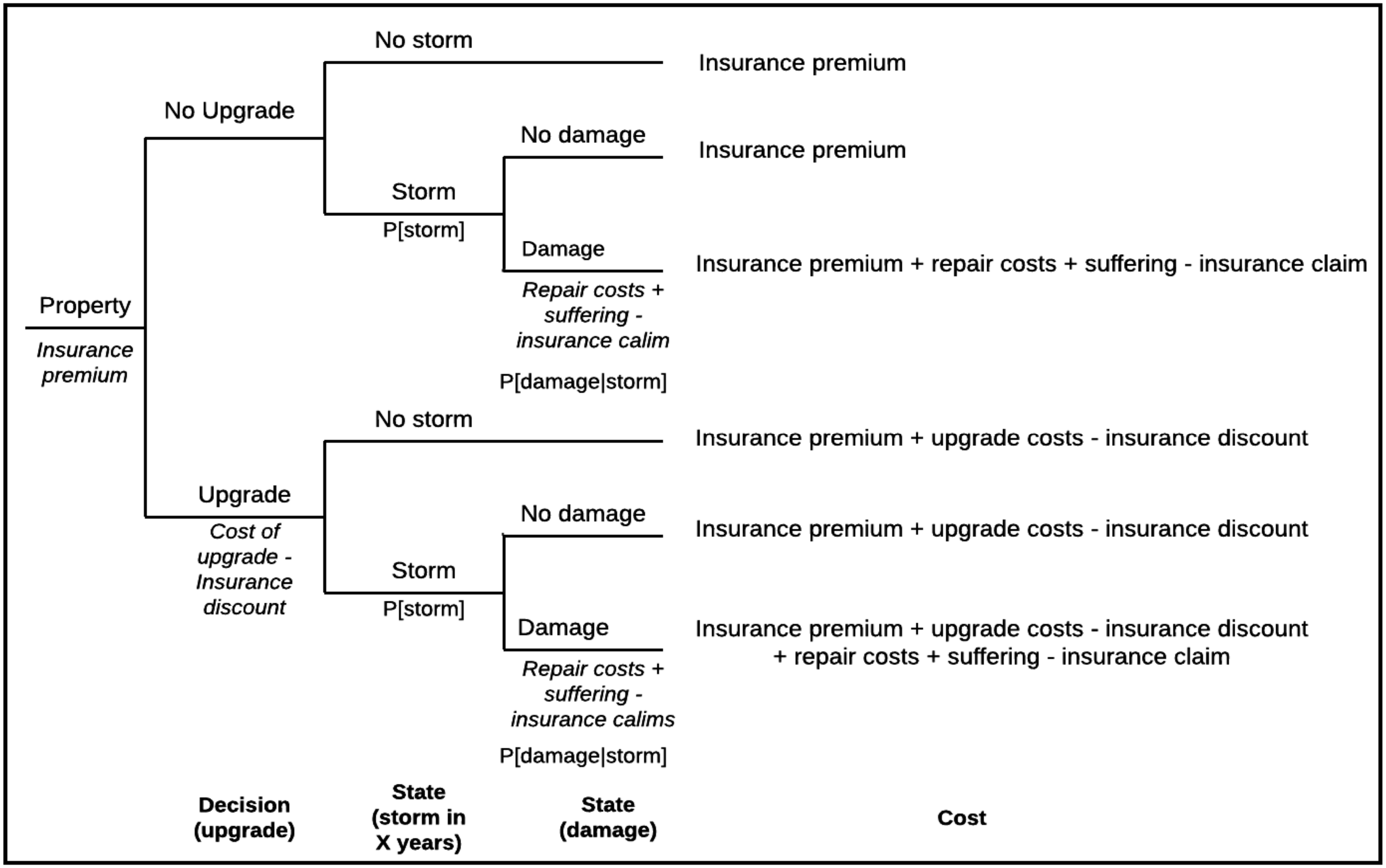

Fig. (5-1): Rational homeowner's decision tree.

Following standard analysis procedures for decision trees, we determine the cost associated with each pathway in the tree. This is done simply by adding any fixed costs associated with the decision and the costs associated with the states. This is explained in more detail in the following.

The decision tree in Figure (5-1) starts on the left side of the figure indicating the initial state of the property and the initial insurance premium for the property. Moving to the right there are two main branches for the two possible decisions made by the homeowner. In the top branch the homeowner decides not to upgrade. This decision has no additional cost to the homeowner. The insurance premium remains unchanged.

In the bottom branch, the homeowner decides to upgrade the house. This decision adds the annual cost of upgrade to the total costs but also causes a reduction in the insurance premium. To compute the annual cost of the upgrade, we use assumptions 5a and c as follows: begin with the total cost of the upgrade; add this cost to the value of the house at the end of the X-year analysis period with no loss due to degradation or inflation; discount to the current value using the discount rate in assumption 5a; and divide the difference between current and discounted future costs by the number of years X during which the costs are distributed to arrive at the final result.

The insurance discount (or reduced insurance premium) is used in the model because, as noted in Chapters 3 and 4, the National Flood Insurance Program (NFIP) encourages homeowners to upgrade their properties by offering reduced insurance premiums to those homeowners who upgrade their houses.

Moving to the right on either branch of the tree, there are two possible states: whether or not there is a storm event in one year during which the expected costs of the homeowner are being evaluated. These possible states divide each one of the main branches of the decision tree into a secondary division with labels "storm" or "no storm."

Each storm has a return period and associated probability of occurrence during one year. According to Bernoulli sequence theory, a T-year storm has a probability of 1/T of occurring each year. This probability is indicated in Figure (5-1) as P [storm]; the complement event of no storm has probability of occurrence 1 – P [storm]. If there is no storm, there will be no damage; therefore, there are no additional costs to be considered in the total costs shown at the right of the figure. If there is a storm, there will be one more division of branches with two possible states after the occurrence of a storm: "damage" or "no damage." The probability of "damage" as a result of a storm is shown as P [damage | storm] in Figure (5-1) and the probability of "no damage" is shown as 1 – P [damage | storm].

If there is no damage to the property, there will be no additional costs for the homeowner; thus, the total cost at the end of each branch will be the same as the case where there was no storm. When damage occurs, however, there will be the cost of repair plus the cost of suffering from flooding (including the clean up after flooding, emotional effects, etc.) minus the repair funds provided by the insurance company through insurance claims.

The total cost associated with each sequence of decision and states is shown at the end of each branch of the decision tree in Figure (5-1). To calculate the expected cost for each decision, we use the utility function as shown in equation (5-1):

$$E\ [C] = C_{state\_1} * P\ [state\_1] + \ldots + C_{state\_n} * P\ [state\_n] \quad (5\text{-}1)$$

Where E [C] is the expected value of cost C, C_{state_j} is the cost associated with state_j, and P [state_j] is the probability of state_j. For the decision tree of Figure (5-1) the expected cost of each decision is determined by considering all possible storms and possible levels of storm damages is calculated in equations (5-2) through (5-6) below.

$$E\ [C \mid upgrade] = \quad (5\text{-}2)$$

$$(\text{Insurance premium} + C_{upgrade} - \text{insurance discount}) * (100\%) +$$

$$P\ [storm] * P\ [damage \mid storm, upgrade] * (C_{repair} - \text{insurance claim} + C_{suffering})$$

Here, E [C | upgrade] is the total expected cost of an upgraded property, $C_{upgrade}$ is the annual cost of the upgrade, C_{repair} is the cost of repair, and $C_{suffering}$ is the cost of suffering.

As noted under assumption 4a.ii, the entire repair cost of the house after flood damage is covered by insurance claim funds, i.e., C_{repair} = insurance claim. Hence, the only remaining cost associated with storm damage is $C_{suffering}$. We simplify equation (5-2) with this assumption, and then include *N* levels of storm intensities and *M* levels of damage as specified in assumptions 1a and 2a to arrive at the following:

$$E\ [C \mid upgrade] = (\text{Insurance premium} + C_{upgrade} - \text{insurance discount}) +$$

$$\sum_{j=1}^{N} \sum_{k=1}^{M} \mathrm{P}\ [\mathrm{storm}_j] * \mathrm{P}\ [\mathrm{damage}_k \mid \mathrm{storm}_j, \mathrm{upgrade}] * \mathrm{C}_{\mathrm{suffering}\ k} \quad (5\text{-}3)$$

Here, damage_k corresponds to damage level_k, storm_j corresponds to storm level_j. The summation, which is the expected cost associated with suffering from storm damage, appears frequently in the analysis that follows. So we introduce the following notation for this important quantity:

$$ES_{\text{upgrade}} = \sum_{j=1}^{N} \sum_{k=1}^{M} \text{P [storm}_j] \ * \ \text{P [damage}_k \,|\, \text{storm}_j, \text{upgrade]} \ * \text{C}_{\text{suffering k}} \quad (5\text{-}4)$$

The expected cost associated with the "no upgrade" decision is similar with two modifications. First, the only fixed cost is the insurance premium. Second, the conditional probability of damage given a storm is changed with the upgrade condition replaced by the no upgrade condition. Numerically, this would result in an increased conditional probability of damage. The result is written as follows:

$$\text{E [C} \,|\, \text{no upgrade] = Insurance premium} + ES_{\text{no upgrade}} \quad (5\text{-}5)$$

$ES_{\text{no upgrade}} =$

$$\sum_{j=1}^{N} \sum_{k=1}^{M} \text{P [storm}_j] \ * \ \text{P [damage}_k \,|\, \text{storm}_j, \text{no upgrade]} \ * \text{C}_{\text{suffering k}} \quad (5\text{-}6)$$

Here, $ES_{\text{no upgrade}}$ is the expected cost of suffering in case of no upgrade in the property.

5.4 Rational Homeowners

At this point we have determined the total cost of each branch of the decision tree; hence, it should be relatively easy to predict the expected behavior of the homeowners. Indeed, this would be the case if all homeowners are rational decision makers who will upgrade their property when the expected cost of the upgrade is less than or equal to the expected cost of no upgrade:

$$\text{E [C} \,|\, \text{upgrade]} \leq \text{E [C} \,|\, \text{no upgrade]} \quad (5\text{-}7)$$

If we substitute the expressions for the expected costs from equations (5-3) to (5-6) and solve for insurance discount, we will have the following result, written in terms of the expected costs of suffering:

$$\text{Insurance discount} \geq C_{upgrade} - (ES_{no\ upgrade} - ES_{upgrade}) \quad (5\text{-}8)$$

On the right side of the equation, the difference of terms in parentheses is the reduction in the expected cost of suffering due to the upgrade; it is the benefit associated with the upgrade. If this benefit exceeds the cost of the upgrade, then the rational homeowner should proceed with the upgrade, even without any insurance discount. If, on the other hand, this benefit is less than the cost of upgrade, then the rational homeowner would proceed with the upgrade only if the discount covers the difference in costs, which is what is shown in equation (5-8). From the point of view of the insurer, the quantity on the right is a fundamental quantity because it defines the minimum discount at which the rational homeowner would consider the upgrade decision. Hereafter, we call this quantity the "Rational discount rate:"

$$\text{Rational discount rate} = C_{upgrade} - (ES_{no\ upgrade} - ES_{upgrade}) \quad (5\text{-}9)$$

It is straightforward to show the above relations graphically. In Figure (5-2), we plot proportion of homeowners who choose not to upgrade as a function of the insurance discount rate. According to the preceding discussion, the rational discount rate is the critical value of interest. If the insurer offers a discount that is less than this critical value, then no one will upgrade; alternatively, if the insurer offers a discount rate that is greater than this value, everyone will upgrade. This is indicated in the figure.

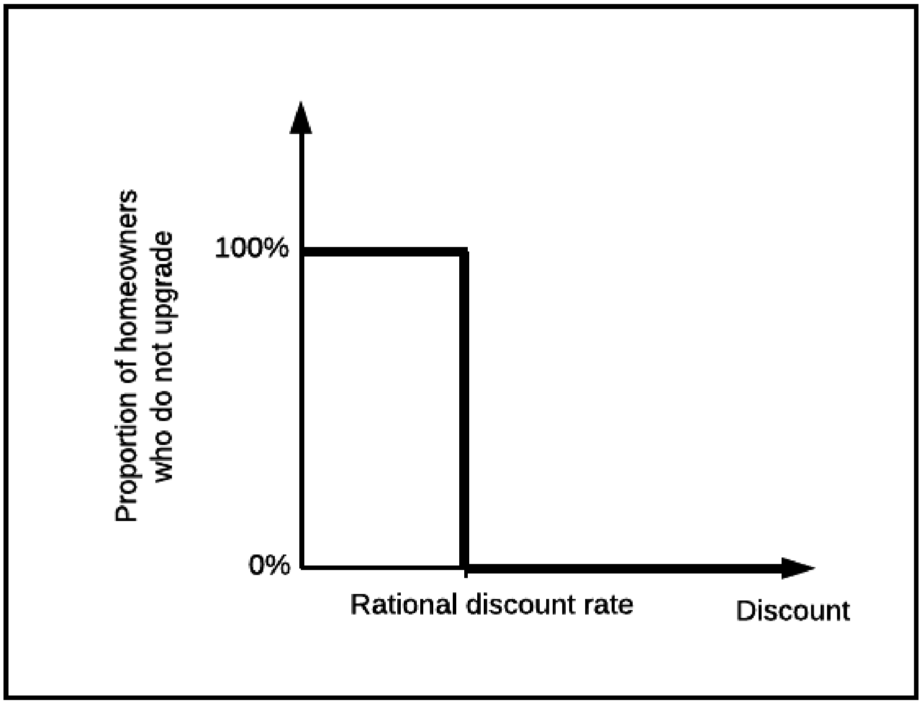

Fig. (5-2): Rational homeowner's behavior in response to the rate of insurance discount.

This binary all-or-nothing homeowner response scenario will occur because at present, all homeowners are modeled with identical behaviors. We have not yet included two important factors: risk aversion and affordability of the homeowner. In the real world, different people have different levels of risk aversion, and different levels of available financial resources for upgrading their property. Risk aversion is the behavior of humans exposed to uncertainty that seeks to reduce that uncertainty. Here, the behavioral option for the homeowners is to upgrade their properties to reduce the risk of flooding. Affordability is an important constraint that can prevent a homeowner to even consider an upgrade, even if an upgrade would lead to lower expected costs. The assumptions underlying risk aversion and affordability, briefly described under assumptions 3b and c, will be examined in detail in the following sections.

5.5 Effects of Risk Aversion

In the previous section we generated a decision tree, calculated expected costs, and determined the condition for which a homeowner would choose to upgrade under the assumption that every homeowner is rational (with no risk aversion) and can afford to upgrade. In this section we analyze the effect of risk aversion on decision making. Affordability is analyzed in the next subsection.

5.5.1 Decision Tree for Risk Averse Owners

Figure (5-3) shows the decision tree with addition of the cost of risk. The risk aversion cost is added to the top main branch where the homeowner decides not to upgrade the house and the house is at a higher risk of flooding compared to the upgraded house. In the bottom branch, the homeowner upgrades the house, and there is no cost of risk associated with this decision. It is noted that if there were two costs of risk, one associated with the no upgrade decision and the other associated with the upgrade decision, we can simply subtract the latter from the former to arrive at a modified cost of risk for the no upgrade decision and zero cost of risk for the upgrade decision. Hence, assumption 3b.i that assigns no cost of risk to the upgrade decision is not limiting.

It follows that the costs associated with the (lower) upgrade branch of the decision tree are identical to those of the decision tree of the rational homeowner in the preceding subsection. Hence, the expected cost given the upgrade decision is also unchanged.

The expected cost given a no upgrade decision differs from the rational homeowner result only by the addition of the cost of risk, denoted as C_{risk}. Hence the result is a slight modification of equation (5-5):

$$E\ [C \mid \text{no upgrade}] = \text{Insurance premium} + C_{risk} + ES_{\text{no upgrade}} \qquad (5\text{-}10)$$

As noted in assumption 3a, the value of C_{risk} is different for each homeowner. Hence, the uniform behavior that was noted for the rational homeowner case in the preceding subsection will no longer hold. A special case to note is the when the cost of risk exceeds the cost of upgrade, $C_{risk} > C_{upgrade}$. In this case, the homeowner would choose to upgrade, regardless of any insurance discount, the cost of risk and the expected cost of suffering associated with no upgrade would exceed the cost of upgrade and the reduced expected cost of suffering given the upgrade.

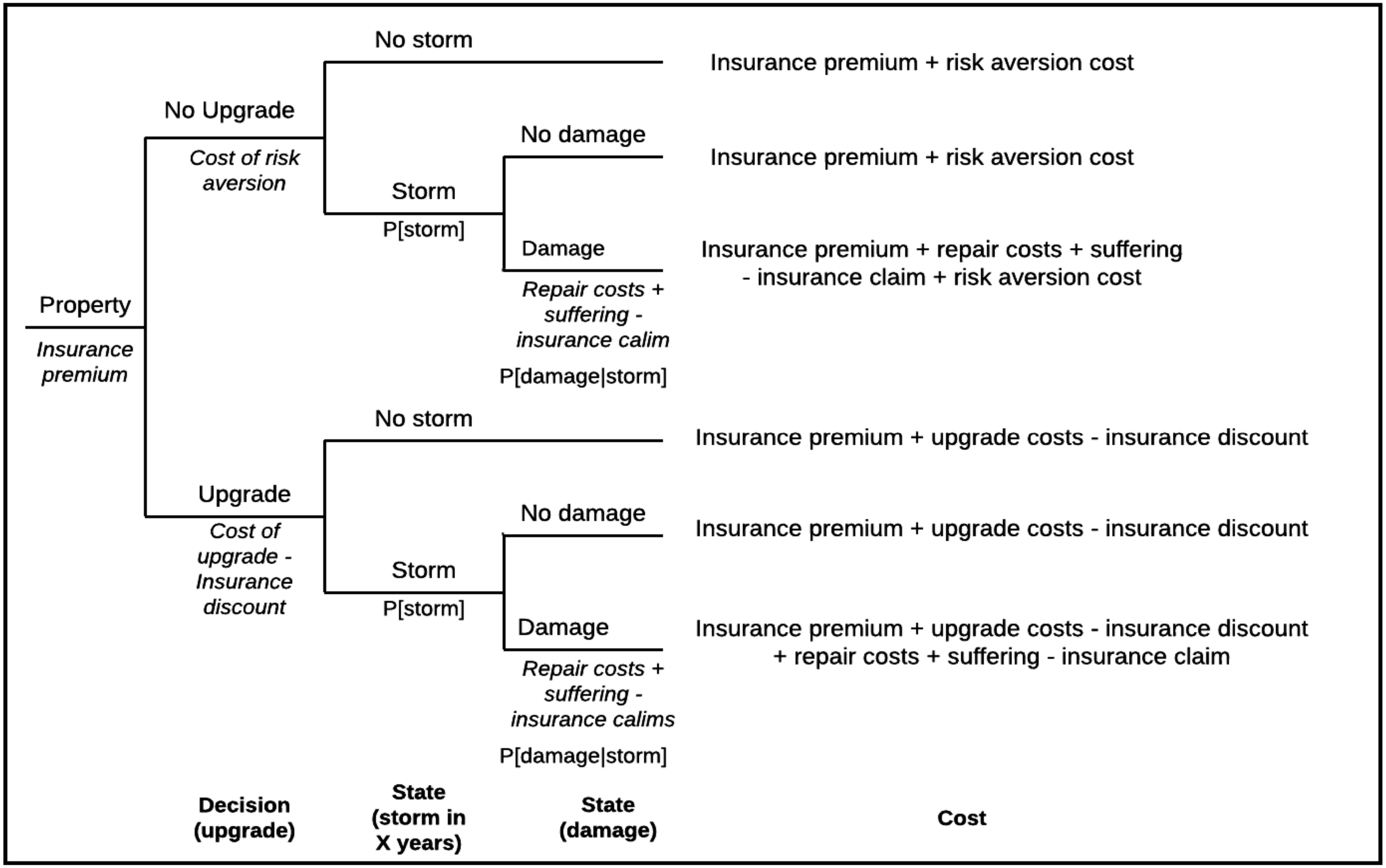

Fig. (5-3): Risk averse homeowners' decision tree.

5.5.2 Effects of the Cost of Risk on Insurance Discounts

We have utilized a log-normal distribution function for the cost of risk of the homeowners. Before we can analyze the effects of the cost of risk on homeowner decision-making with respect to the insurance discount rate, it is necessary to quantify the variability in the costs of risk. This is done by using a cumulative distribution function (CDF). Figure (5-4) shows the diagram of the CDF, F (C_{risk}), for the cost of risk for risk-averse homeowners. The diagram shows the proportion of homeowners with cost of risk $\leq$ C (e.g., as indicated on the diagram, 80% of homeowners have cost of risk $\leq C_{risk\ 1}$). The cumulative distribution function is simply the normalized integral of the histogram of C_{risk} for all homeowners.

A variety of parametric models can be used for this CDF; the only restriction is that the cost of risk should always be positive. (We do not allow homeowners to prefer higher risk of storm damage.) Herein, we use the log-normal distribution.

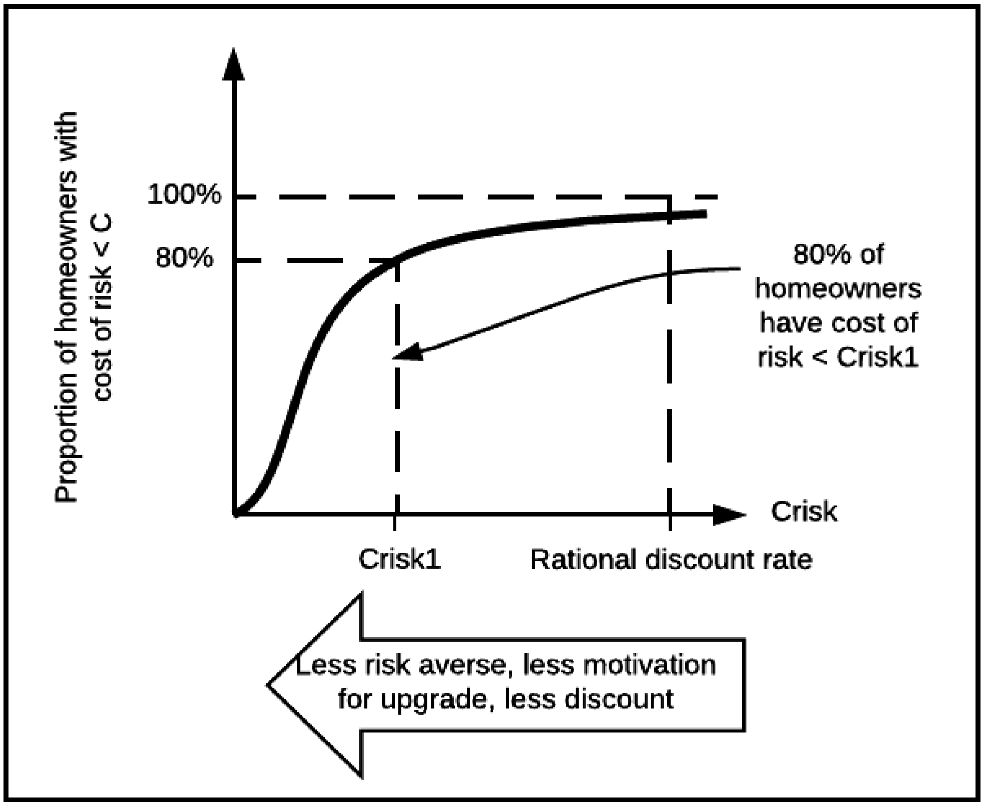

Fig. (5-4): Cumulative distribution function (CDF) of cost of risk for risk-averse homeowners.

If we substitute equation (5-10) into equation (5-7), we will have the following condition for homeowners choosing the upgrade option:

$$\text{Insurance discount} + C_{risk} \geq C_{upgrade} - (ES_{no\ upgrade} - ES_{upgrade})$$
$$= \text{Rational discount rate} \qquad (5\text{-}11)$$

Compared with the inequality in equation (5-9) for the rational homeowner, it can be seen that the required discount needed to induce homeowners to upgrade is lower than before, by the amount C_{risk}. In other words, the cost of risk acts as a supplement to the insurance discount. If the sum of these two quantities is equal to the rational discount rate, then the homeowner is indifferent with respect to the upgrade decision; when it is smaller, the homeowner will not upgrade, otherwise the homeowner will upgrade.

Since the cost of risk is different for each homeowner, we will need to determine the proportion of homeowners who will choose to upgrade or not upgrade. It is simpler to consider the latter because it is compatible with the definition of the CDF:

Proportion of homeowners who will not upgrade (5-12)

= Proportion of homeowners with C_{risk} < Rational discount rate – Discount

= F (Rational discount rate – Discount)

Figure (5-2) needs to be modified to include this CDF. This is done by introducing the CDF of the cost of risk into the figure, as shown in Figure (5-5) and as explained in the following. The dashed line is taken from Figure (5-2); it represents the proportional of rational homeowners who do not choose the upgrade option. This corresponds to the case when $C_{risk} = 0$, with a vertical line to 100% at the rational insurance discount rate. Below the horizontal axis, there are two braces indicating a discount and C_{risk} that add up to the rational insurance discount. As noted after equation (5-11):

- If Insurance discount + C_{risk} = rational insurance discount, then the homeowner is indifferent to the upgrade decision.
- For smaller values of C_{risk}, the homeowner will not upgrade. Hence, in the figure, the proportion of homeowners who will not upgrade should correspond to the CDF of C_{risk}. This implies that the large vertical arrow shown in the figure should be equal to F (C_{risk}) and should be placed at a distance C_{risk} to the left of the rational insurance discount.

Hence, the CDF is plotted in the reverse direction, with F (0) plotted at the rational insurance discount, as shown.

- The height of this curve is the proportion of households that choose not to upgrade, and the distance from the curve to the 100% level is the remaining proportion of households who do upgrade.

This diagram shows that even when there is no insurance discount, a proportion of the homeowners with a high degree of risk aversion will decide to upgrade their house. As the discount rate increases, more homeowners find it reasonable to upgrade. When the rate of insurance discount reaches the rational insurance discount of equation (5-11), then all homeowners decide to upgrade their homes. This is expected because this point corresponds to $C_{risk} = 0$, which defines the rational homeowner; we already know that such homeowners will decide to upgrade at the rational insurance discount.

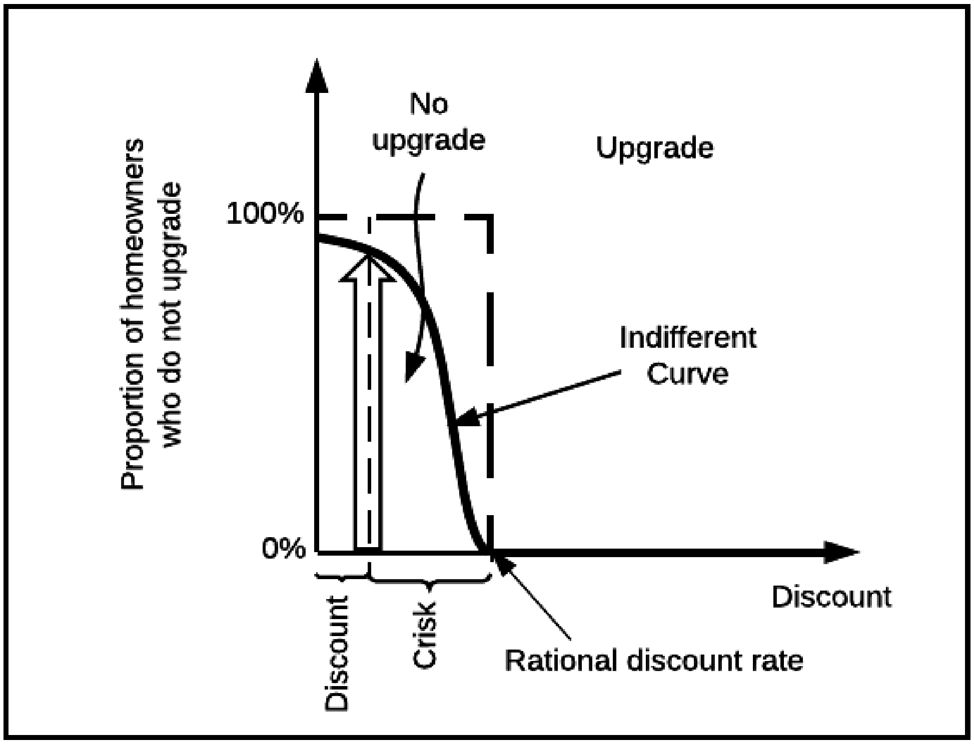

Fig. (5-5): Risk-averse homeowner's behavior in response to the rate of insurance discount.

5.6 Effects of the Affordability Constraint

In the analysis of the preceding subsection, we assumed that all homeowners can afford the upgrade. In reality, a proportion of homeowners may not be able to afford to upgrade even at high levels of insurance discounts. In the present section, we introduce affordability into the equations and discuss how it affects the decisions of homeowners.

Figure (5-6) shows a sample CDF of affordability, plotted with respect to the insurance discount rate. It can be seen that when there is no discount, then only 20% of the homeowners have the resources to consider the upgrade option. When the discount is set at $r_{discount1}$, then this proportion increases to 80%.

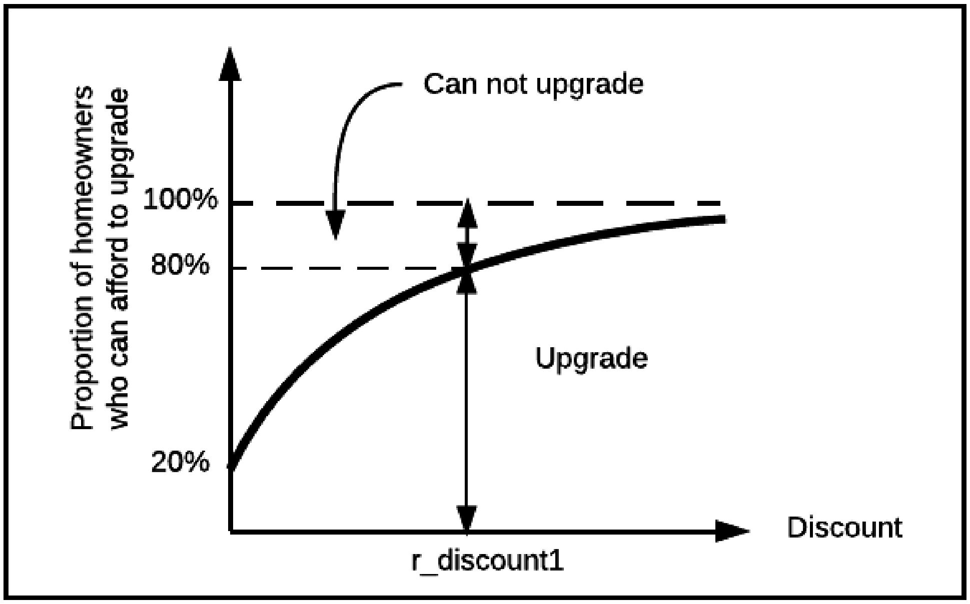

Fig. (5-6): Cumulative distribution function (CDF) of homeowners' affordability to upgrade.

To be consistent with previous diagrams, it is convenient to show the proportion of homeowners who <u>will not</u> upgrade. This is simply the complement of the CDF, as shown in Figure (5-7), in which the vertical axis shows the proportion of homeowners who cannot afford to upgrade.

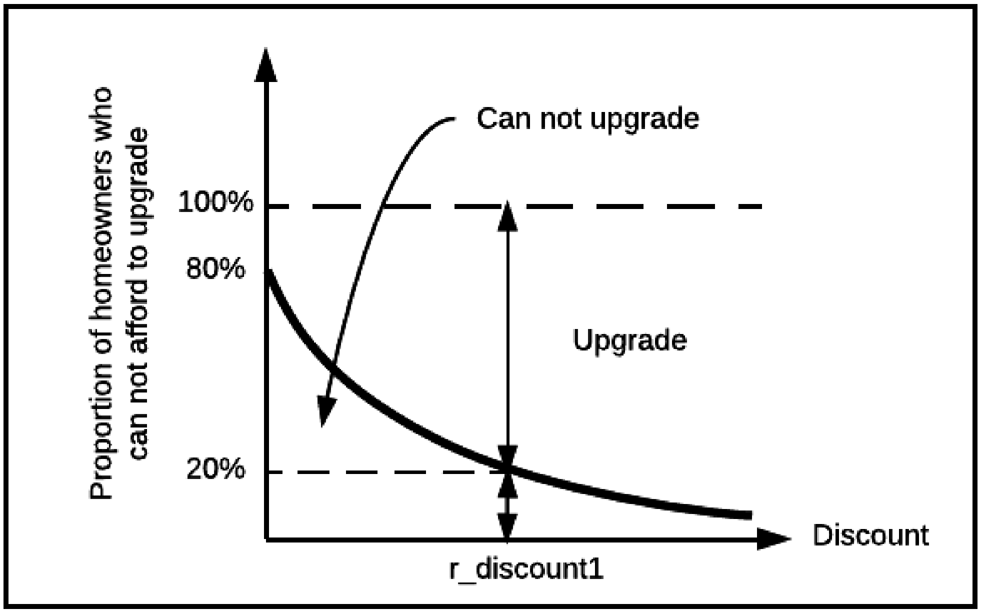

Fig. (5-7): Complementary cumulative distribution function (CCFD) of homeowners' affordability to upgrade.

As noted in assumption 3c, the affordability constraint will affect the homeowners' decisions to upgrade regardless of the expected costs associated with upgrading and not upgrading. Hence, even the most risk averse homeowner will not be able to upgrade if this option is unaffordable. Figure (5-13) is a modification of Figure (5-5) that accounts for this effect of affordability. The dashed line curve is the proportion of homeowners who will not upgrade, when affordability is not accounted for, i.e., it is the curve shown in Figure (5-5). The solid curve is the proportion in which the affordability constraint is included. The difference between these curves is related to the proportion of homeowners who cannot afford the upgrade, as indicated by the close-up shown in the figure.

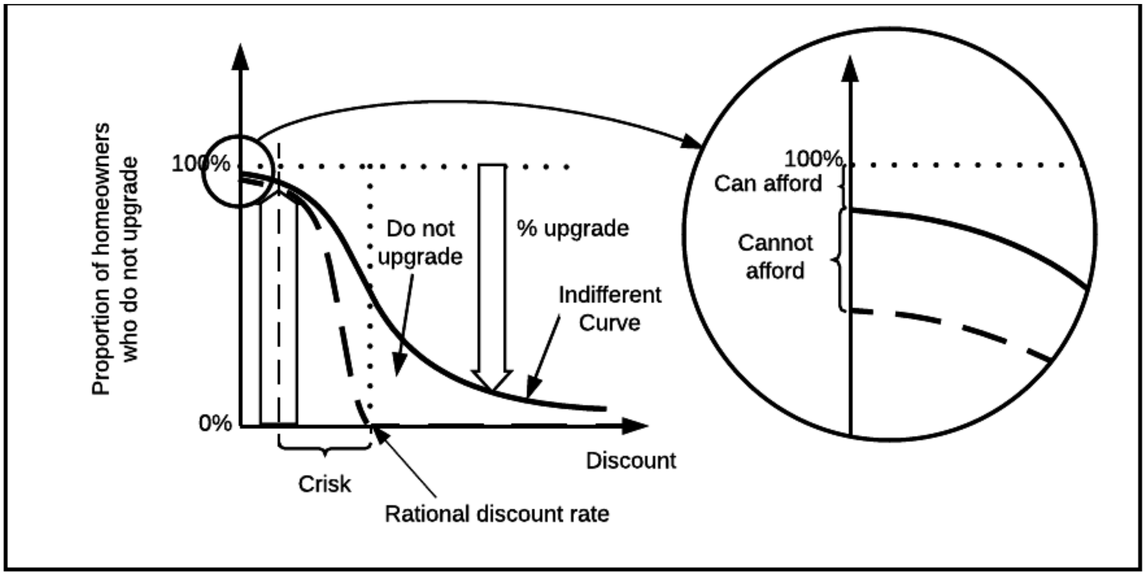

Fig. (5-8): Risk-averse homeowner behavior in response to the rate of insurance discount and accounting for upgrade affordability.

5.7 Optimal Flood Insurance Discount

Figure (5-8) of the previous section shows the proportions of homeowners who will upgrade or not upgrade their homes in response to the insurer discount rates. The insurer can use this information to adjust their discount rate to minimize loss, thereby satisfying assumption 4b.i. The insurer would also use this same information to set insurance premium rates so that they would not experience any net profit or loss, to satisfy assumption 4b.ii. The two conditions, minimized and zero loss, are actually coupled through this diagram, as explained in the following.

To begin, we compute total loss. First, we define the expected costs of repair of a single residence, given that the residence is upgraded and not upgraded:

$$\mathrm{ER}_{\mathrm{upgrade}} = \sum_{j=1}^{N} \sum_{k=1}^{M} \mathrm{P}\ [\mathrm{storm}_j] * \mathrm{P}\ [\mathrm{damage}_k \mid \mathrm{storm}_j, \mathrm{upgrade}] * \mathrm{C}_{\mathrm{repair,k}} \tag{5-13}$$

$$\mathrm{ER}_{\mathrm{no\ upgrade}} = \sum_{j=1}^{N} \sum_{k=1}^{M} \mathrm{P}\ [\mathrm{storm}_j] * \mathrm{P}\ [\mathrm{damage}_k \mid \mathrm{storm}_j, \mathrm{no\ upgrade}] * \mathrm{C}_{\mathrm{repair,k}} \tag{5-14}$$

Then, for every discount and for every proportion of non-upgrading households, the loss is given by scaling the above expected costs by the proportion of households that opt to upgrade (P_{upgrade}) and not upgrade ($P_{\mathrm{no\ upgrade}}$), summing the results along with the discount, which also must be scaled by P_{upgrade}, and subtracting the insurance premium fee, which offsets the loss:

$$\mathrm{Loss} = \mathrm{ER}_{\mathrm{upgrade}} * \mathrm{P}_{\mathrm{upgrade}} + \mathrm{ER}_{\mathrm{no\ upgrade}} * \mathrm{P}_{\mathrm{no\ upgrade}} - \mathrm{fee} + \mathrm{discount} * \mathrm{P}_{\mathrm{upgrade}} \tag{5-15}$$

In Figure (5-9) the contours of loss are shown along with the curve, from Figure (5-8) of the proportion of non-upgrading homeowners. The general trend in the insurer's loss is indicated in the figure: losses increase in the upward direction because there is a larger proportion of households that do not upgrade, leading to an increase in the expected cost of repair. Losses also increase in the rightward direction because of the larger rates of discounted premiums for upgraded properties. The optimum discount rate is where the household indifference curve and the loss contours meet at the lowest expected cost for the insurance company. This point is marked by r^*_{discount} in Figure (5-9) and is the point of tangency between the two sets of curves.

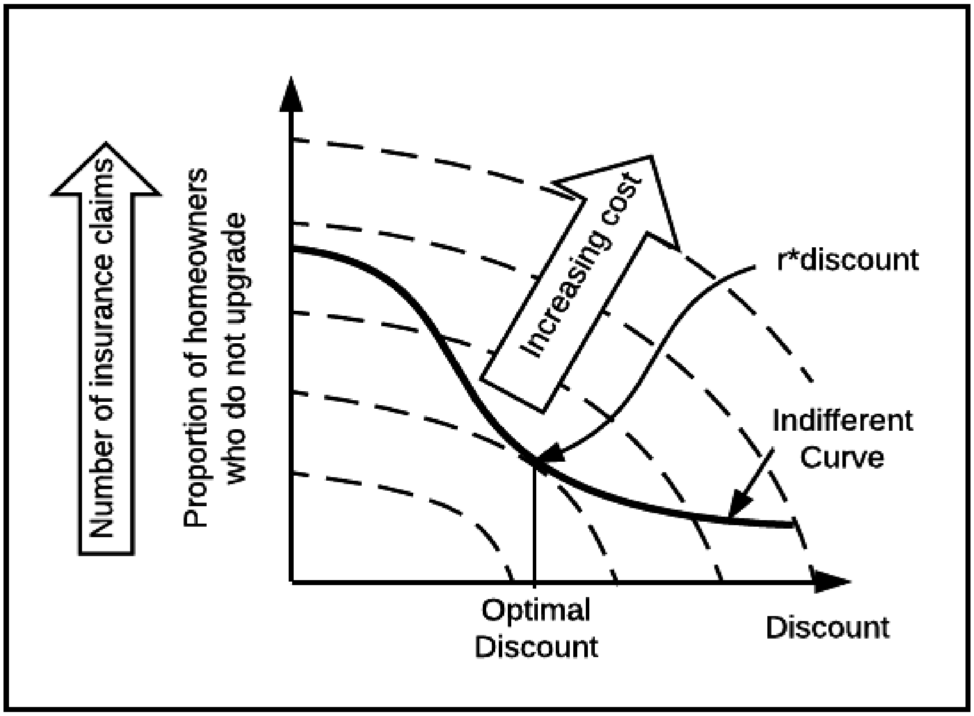

Fig. (5-9): Insurance losses and the optimal discount rate.

5.8 Time Series

It is customary to view costs using a time-series plot, in which the horizontal axis is time and the vertical axis is some measure of cumulative cost. This would be for a particular realization of the computational ABM, as described in the following:

- Each year is characterized by either no storms or a storm at a particular intensity, as determined by the Bernoulli sequence model for the storms.
- If there is a storm in any given year, then each residence is characterized by some level of damage (including the possibility of no damage), as determined by the conditional probabilities of damage given the upgrade or no upgrade status of the residence.

- Once these damage states are determined, then the repair costs are computed for each residence and summed.
- The insurer's reserve is computed by summing all collected insurance fees (minus any discounts) and subtracting the costs of repair.

Figure (5-10) is an illustration of how these results can be shown with time-series plots. The solid line in the upper plot of the figure shows the gradual accumulation of the insurer's reserves with time due to the yearly collection of fees. The slope of this line is equal to the sum of all household insurance premium fees minus any discounts. Sharp drops in the reserves occur with each storm because of the cost of repairs of residences damaged by the storm. The magnitude of each drop is equal to the total cost of repair for each storm.

If we include changes in the insurance fees and the discount rate, which are plotted in the middle and lower plots of the figure, then the slope of the insurance reserves plot would change. An increase in fees may be needed if the repair costs and/or storm frequency are higher than expected, and an increase in the discount rate may be needed if the number of upgrades is lower than expected. The growth of insurers' reserves after increasing the rate of discount is illustrated with a dotted line in Figure (5-10). As expected, the dotted line has a smaller slope due to the reduced rates. However, the drop in reserves during a storm event is expected to be smaller in magnitude due to an increase in the number of upgrades and the associated lower cost of repair. If the insurers increase the insurance premiums, the insurance reserves will grow more rapidly and the slope of the line will increase as shown with a dashed line in Figure (5-10). These changes in the insurance fees and discount are shown here for illustrative purposes only; while they would be straightforward to implement, they are not considered any further in this thesis until the last section, where we discuss future research.

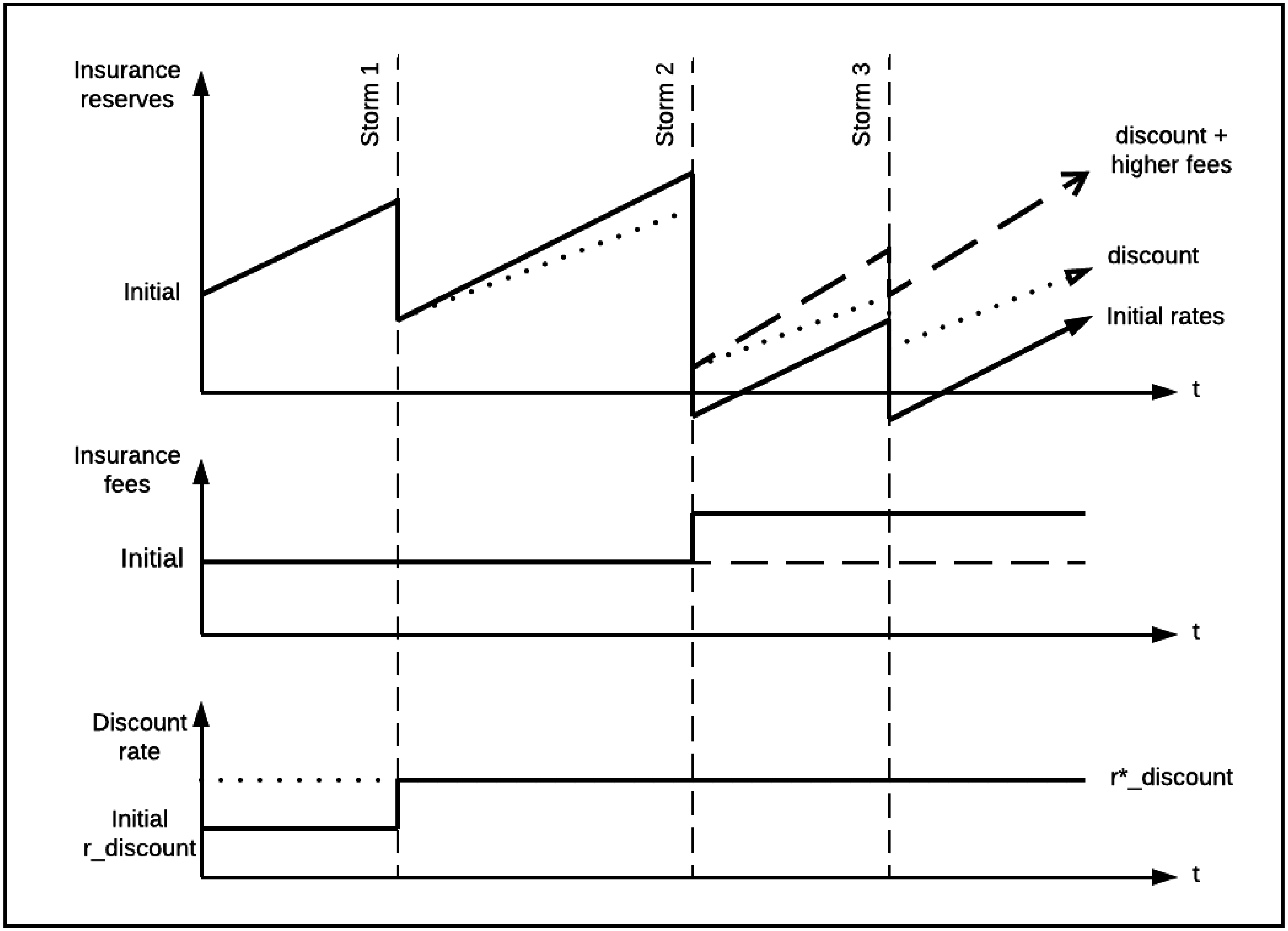

Fig. (5-10): Time series of the insurance company reserves, and the associated fees and discount rates.

5.9 Community Upgrade: Flood Control Measure

Implementing a flood control measure can have a significant impact on improving coastal resiliency and reducing the risk of coastal flooding. After the addition of a flood control measure, the probability of damage after a storm event decreases for both upgraded and not upgraded properties. Furthermore, a measure may lead to a change in the flood zones, which will decrease the flood insurance premiums for the residents of the community. In our computational ABM, we assume that all of the houses are in the same flood zone with similar risk of flooding (assumption 1b) and all homeowners pay the same flood insurance premiums with the same discount if the residence is upgraded (assumption 4a). We also assume the addition of a flood control measure offers the same reduced probability of damage for each storm intensity for all non-upgraded residences, with a similar statement also applying for all upgraded residences (assumption 2b).

It may appear that a measure, with its protective capabilities, would automatically result in decreased cost savings for everyone in the community. This is not necessarily true. There are several feedback mechanisms within the system that cause the improved resilience of the community to be less than what may be expected from a community measure. To understand this more fully, we examine the impacts of a community measure on costs and homeowner decision-making in more detail in the following sections.

5.9.1 Cost of Community Upgrade

In the conceptual model develop in Chapter 3, we noted that the cost of building flood control measures are often partially covered by Pre-Disaster Mitigation grants (PDM) provided to the local communities by the government, with the local community covering any remaining costs. We also noted that community residents pay taxes to the community as well as to the government. For the computational ABM, we simplify these relations consider the cost of building a measure to be equally divided between the homeowners of the coastal community in which the measure is to be built (assumption 4a.iv). The cost is collected from the homeowners as an additional fee, which we call a “measure fee.” This measure fee will be added to the insurance fee and will result in an increase the total costs to the homeowners; hence this fee may affect their financial ability to upgrade their property, as determined by each homeowner’s affordability (assumption 3c). Building the measure, however, will decrease the probability of flood damage and associated costs of damage, which will lead to two counteracting effects: First the reduced cost of damage would lead to a decrease in the insurance fee. Since the reduced costs would apply to both houses with and without upgrade, then, according to equation (5-12), there may be more homeowners who opt not to pay for an upgrade, which would tend to increase expected costs of repair, leading to an increase in the insurance fee. Clearly there are many interacting effects that will occur with the introduction of a community flood-protection measure. These multiple effects are more easily understood through a series of diagrams and examples, which are presented in section 5.10.

5.10 Utility of the Measure at the Homeowner and Community Levels

The computational ABM handles the decision rules of the homeowners who must choose between upgrading and not upgrading as well as the insurer who must set fees and discounts. The decision of proceeding with a community measure is more subtle. We will not be able to address this topic until Chapter 7, where we bring in tools of quantitative sociology. To prepare for this analysis, we will need a measure of utility.

We express the utility for homeowner i in the form of a Cobb-Douglas utility function that contains a term associated with the homeowner as an individual and the homeowner as a member of the community:

$$U_i = U_{i,\text{individual}}^{1-x_i} U_{\text{community}}^{x_i} \tag{5-16}$$

Here, $U_{i,\text{individual}}$ is the utility of the homeowner as an individual expressed in terms of some level of resource R_i minus all net costs associated with storm hazards:

$$U_{i,\text{individual}} = R_i - \mathrm{E}[C_i \,|\, \text{upgrade status}_i, \text{no measure}] \tag{5-17}$$

$$U'_{i,\text{individual}} = R_i - \mathrm{E}[C_i \,|\, \text{upgrade status}_i, \text{measure}]$$

We use the prime to indicate a community with a protective storm measure. Upgrade status_i refers to either upgrade or no upgrade, which is determined for homeowner i through the computational ABM.

The utility of the homeowner as a member of the community is expressed in one of two ways. The first is simply by using the average of the above:

$$U_{\text{community}} = \bar{R}_i - \overline{\mathrm{E}[C_i \,|\, \text{upgrade status}_i, \text{no measure}]} \tag{5-18}$$

$$U'_{\text{community}} = \bar{R}_i - \overline{\mathrm{E}[C_i \,|\, \text{upgrade status}_i, \text{measure}]}$$

The other way is to use the average monetary of the households to pay for the insurance, any measure and any upgrade. This includes the insurance fee minus the discount, in which the discount is only for households that upgrade and the fee includes any cost of the measure. These are the monetary cost that are not related to suffering and risk, and would correspond to the first few terms of equations (5-3) and (5-5):

$$U_{\text{community}} = \bar{R}_i - \text{Insurance fee} - \overline{(C_{\text{upgrade},i} - \text{discount}_i)} \tag{5-19}$$

$$U'_{\text{community}} = \bar{R}_i - \text{Insurance fee}' - \overline{(C_{\text{upgrade},i} - \text{discount}_i)}$$

With our computational ABM, we are able to obtain values for all of the above terms that are needed to find the utilities in equation (5-16), given the values of the individual resources R_i and the exponents x_i. In the results presented herein, we use a common value for the resource R_i that is sufficiently high so that the utilities are always positive. The exponent x_i represents the degree of interest of homeowner i in supporting community activities such as the financing and construction of a storm-protective measure. This exponent has the following interpretation:

$x_i = 1$: utility based only on community welfare, with no interest in self

$x_i = 0$: utility based only on self, with no interest in community welfare

$0 < x_i < 1$: utility that includes both self and community interests.

As x_i increases from 0 to 1, then the homeowner utility U_i varies from $U_{i,\text{individual}}$ to $U_{\text{community}}$. Hence, this exponent can be viewed as the degree to which the homeowner acts in the interest of the community. In the next section, the behavior of the homeowner utility U_i as a function of the exponent x_i will be illustrated through a series of numerical examples.

5.11 Summary

In this chapter we utilized decision theory in our agent-based model (ABM) and modeled several scenarios to provide an understanding into different aspects of community resilience. We were able to derive mathematical relationships for the key economic quantities that govern individual and insurer decisions, including the fees to set for insurance, discounts to offer for those that upgrade their homes, and the decisions for the homeowners regarding residential upgrades and the financial support of a community flood-mitigation measure. We were also able to describe the emergent economic behaviors of the actors through a sequence of level-plots. In the next chapter, we present a parameter study to illustrate these results through a series of example scenarios.

Chapter 6

Parameter Study of Storm-Surge Resilience

6.1 Introduction

In this chapter, we present a series of results generated by the computational ABM described in Chapter 5. These results illustrate how the ABM can be used to assess the impact of the effectiveness and cost of the upgrades and measure and the costs associated with repair and suffering.

An outline of the ABM runs is given the following:

1. Baseline. Here we describe the parameters of the ABM in detail and explain the meaning of the plots generated by the model. In this and all other cases below, we begin with a model run in which there is no community measure before proceeding to the case where there is a measure.

2. Less costly property upgrades.
    a. No change in upgrade effectiveness. In this case, we decrease the cost of residential upgrades by 30%, as compared with the baseline runs. The effectiveness of the upgrades is unchanged.
    b. More effective property upgrades. The difference between this case and the preceding case is that we consider more effective upgrades, in which the probability of damage given a storm is reduced by 40%.
    c. More effective property upgrades with a more costly measure. Here, we increase the cost of the measure by a factor of two, while keeping all of the other parameters of the preceding case the same.
3. More effective measure. This case differs from the baseline case in that the measure is twice as effective, in which the probability of damage given a storm is reduced by 50%.
4. Higher cost of repair. Here, the difference from baseline is in the cost of repair: this cost is doubled.
5. Higher cost of suffering. The cost of suffering is increased by 60% while all other parameters are the same as the baseline case.

6.2 Baseline without the community measure

We begin the description of the baseline case by briefly summarizing the computational procedure in the ABM. In our ABM we have considered a fairly uniform community in which all homes have a similar risk of flooding, insurance premium rates, cost of upgrade, and probability of damage. The cost of risk and affordability are not equal for all homeowners in our model and are distributed using lognormal, and normal distribution functions, respectively. The model is run with no flood control measure and again after adding a flood control measure.

The ABM generates intermediate results for a range of values for the insurance premium rates. For each value of the premium, the ABM calculates the rational discount rate, plots the indifference curve and solves the equations to calculate the expected costs of repair and suffering. The ABM then determines the contours of the insurer's cost and finds the optimal discount rate by finding the point where the indifference curve intersects the contour of the insurer's cost with the lowest cost. The ABM then determines what proportion of the community is upgraded.

We have assumed the insurers are not-for-profit and operate so that they do not incur long-term expected losses. To achieve these goals, the intermediate results with varying insurance premiums are used to determine, by linear interpolation, the insurance premium rates that lead to no profit; we call this the "optimal premium rate," hereafter. The ABM is then run once again at the optimal premium rate to determine the optimal discount rate, the upgrade status and expected costs of each homeowner, and checks that the insurer profit is close to zero. In the following, we only show the results corresponding to the optimal premium rate.

We have showed expected costs of intangibles such as suffering and risk in terms of US Dollars (USD) on the plots to make the results easier to interpret. In this manner, we can see how the model outputs depend on input variables, such as the insurance premiums and upgrade costs, with the same units of value.

The ABM results are presented in the following sections for all cases listed in the introduction with and without a community flood control measure. We begin with the baseline case with input variables as shown in the Table (6-1) below; then, we changed the input variables one by one or in combinations to model different scenarios and see how they affect the ABM outcome.

It should be noted that for each house, whether upgraded or not upgraded, two levels of damage have been considered in the model: low- or high-level damage. The probabilities of damage for upgraded houses have been considered to be six times smaller than those of non-upgraded houses. Hence, we have used a probability reduction factor to create the matrix of probability of damage for upgraded houses.

$$P\,[\text{damage}_k \mid \text{storm}_j, \text{upgrade}] = P\,[\text{damage}_k \mid \text{storm}_j, \text{no-upgrade}] \,/\, 6 \qquad (6\text{-}1)$$

Similarly, after adding a measure to the community, the probabilities of damage after each possible storm event will decrease. This decrease in probability of damage is calculated by a matrix factor as shown in Table (6-1).

In Table (6-1), the time period for distributing the cost of upgrades and any measure is 10 years; this is the time period in assumption 5a, Chapter 5. An upgrade is assumed to raise the value of the house; hence the net cost is the difference between the present cost of the upgrade and the discounted future value, distributed over 10 years. In this calculations, we used a monetary discount value of 5%. Like all other model input variables, the value for the monetary discount rate can be modified; for instance, this value may be as high as 20%. The cost of construction and maintenance of a flood control measure is added to the total annual costs for all homeowners.

Table (6-1): Parameter values for the baseline case.

Description	**Values**
Insurance premium rate	Intermediate runs: $0, $1K, $2K, $3K, $4K, or $5K/year; final result obtained using the no profit/no loss condition.
Yearly probability of storm	0.005, 0.01, and 0.02 (for the 200-, 100-, and 50-year storms)
P [damage $_{low}$ | storm, no upgrade]	0.09, 0.15, 0.40 (for the 200-, 100-, and 50-year storms)
P [damage $_{high}$ | storm, no upgrade]	0.90, 0.45, 0.15 (for the 200-, 100-, and 50-year storms)
Reduction in the probabilities of damage for upgraded residences	0.17
Reduction in the probabilities of damage after adding a community protection measure	0.7, 0.3, 0.1 (for the 200-, 100-, and 50-year storms)
Cost of suffering	80K, 20K (for high and low damage)
Cost of repair	90K, 20K (for high and low damage)
Time period for distributing the cost of the upgrade and measure	10 years
Monetary discount rate	5%
Cost of upgrade	40K
Cost of upgrade – discounted future value, distributed over the above time period.	1.5K/year
Cost of measure per house	$500/year
Number of houses in the community	9000

Figure (6-1) shows the probability density function (PDF) and the cumulative distribution function (CDF) for the cost of risk of the community residents. The CDF values generated by the ABM are plotted as red dots. The blue lines show the theoretical values for the PDF and CDF. The graphs shown in Figure (6-1) remain the same for all cases in this chapter.

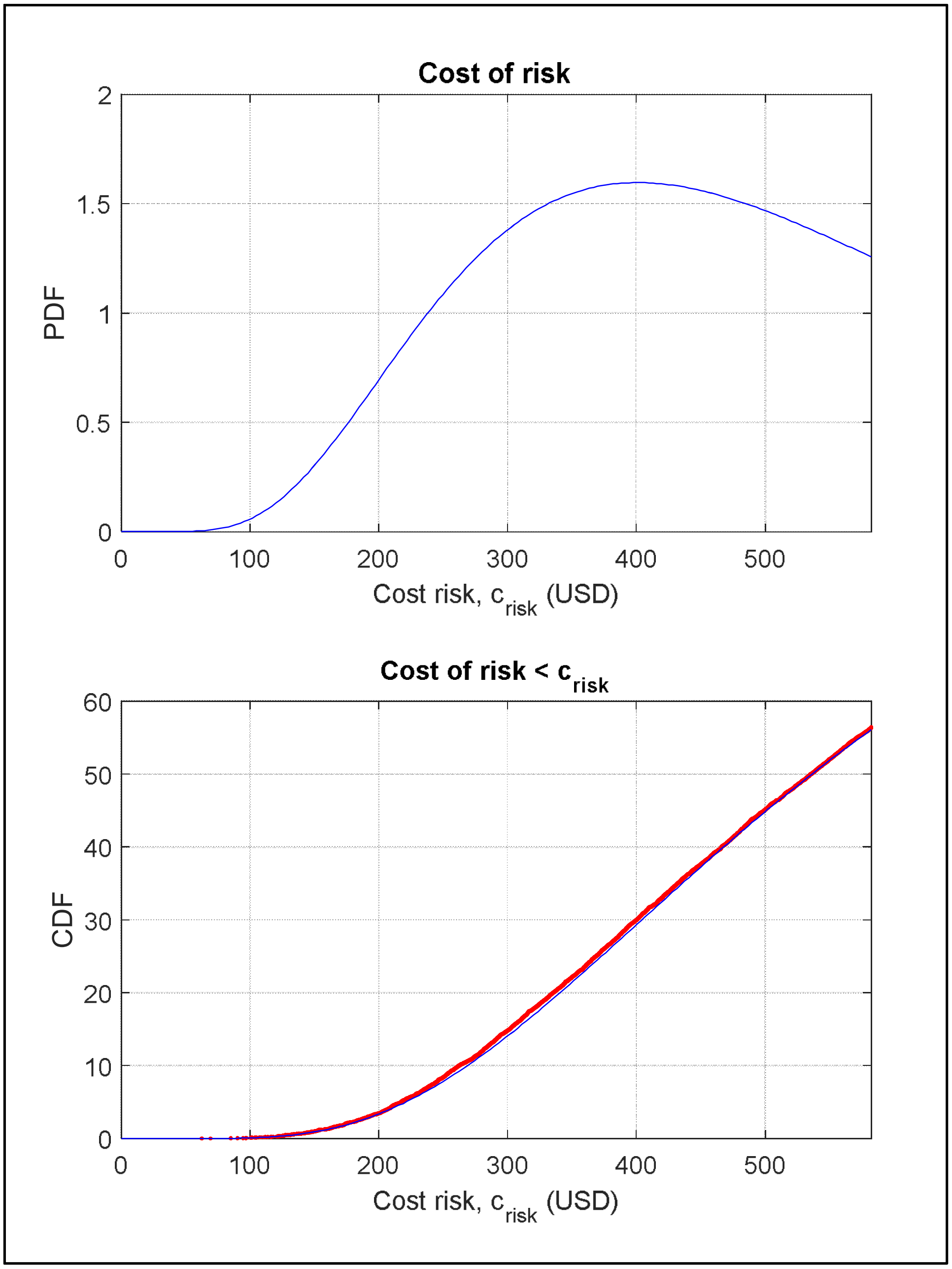

Fig. (6-1): PDF and CDF of the homeowners' cost of risk.

Table (6-2) shows a summary of the results from the baseline model when there is no flood control measure.

Table (6-2): ABM results for the baseline case without community measure.

Description	**Values**
$ES_{no\ upgrade}$	\$1159/year
$ES_{upgrade}$	\$197/year
$ER_{no\ upgrade}$	\$1279/year
$ER_{upgrade}$	\$217/year
Rational discount rate	\$582
Optimal annual insurance premium rate	\$821
Optimal annual discount	\$338
Homeowners' expected annual cost per house	\$2335
Proportion of homeowners who don't upgrade	36%

Figure (6-2) shows the probability density function (PDF) and the complementary cumulative distribution function (CCDF) for the affordability of the community residents to upgrade, as a function of the insurance discounts. The values generated by the ABM are plotted as red dots. The blue lines show the theoretical values for the PDF and the CCDF. We have plotted the CCDF rather than the CDF to follow the analysis process described earlier for determining the optimal discount rate (as shown in Figures 6-6 and 6-7).

The total annual costs for the homeowners will depend on the base insurance premium, tax associated with any measure which is added to the premium, and the level of discount for upgrades. Figure (6-3), which is nearly identical to Figure (6-2), shows how the affordability of homeowners changes according to the level of discount in insurance premiums. As expected, a higher proportion of homeowners can afford an upgrade as the insurance discount increases. The only difference in Figure (6-3) is the addition of a vertical line showing the rational discount rate as calculated in equation (5-9).

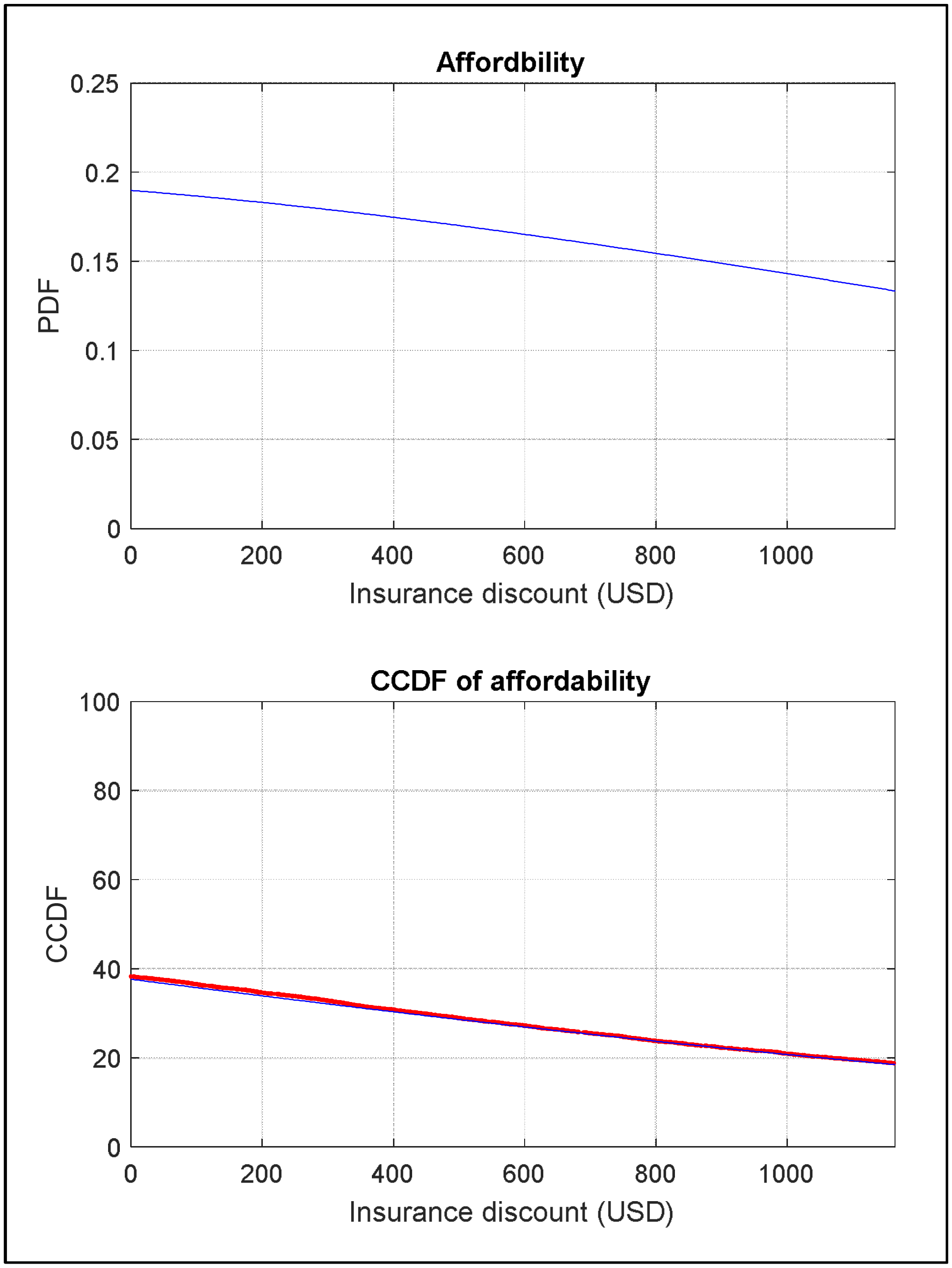

Fig. (6-2): PDF and CCDF of homeowners' affordability to upgrade as a function of insurance discount.

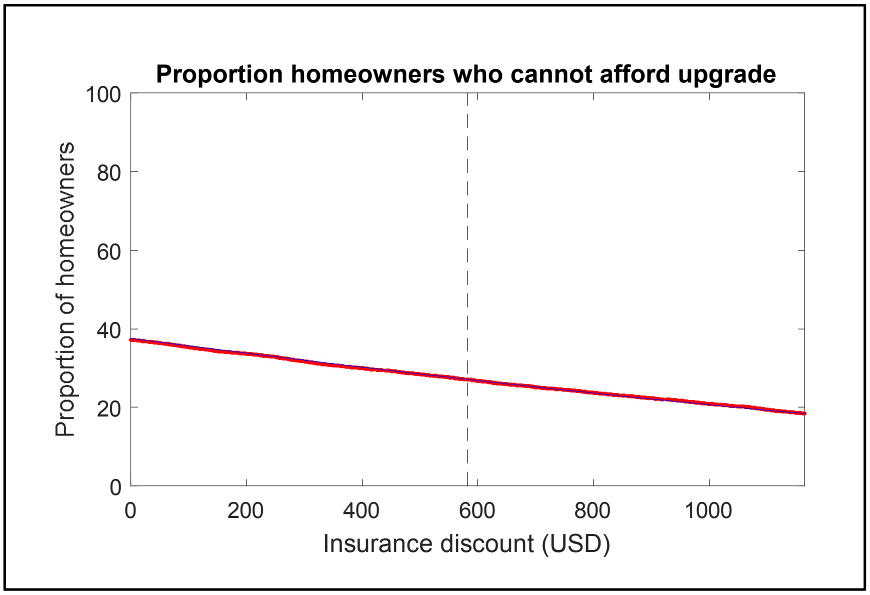

Fig. (6-3): Proportion of homeowners who cannot afford to upgrade as a function of the insurance discount, plotted along with the rational discount rate.

The top graph in Figure (6-4) shows the indifference curve before (blue line) and after (red line) considering the affordability of the homeowners. The vertical dashed line shows the rational discount rate; these curves correspond to those shown in the theoretical development in Figures (5-5) and (5-8). In the bottom graph of Figure (6-4), the indifference curve is plotted over a contour plot. The contours correspond to various levels of the costs for the insurer that were used in Figure (5-9) and are computed using equation (5-15). It was noted that the tangent point of intersection of the indifference curve with the contour of the lowest cost for the insurer determines the optimal discount rate and the proportion of households that choose not to upgrade. This point is indicated by a red circle in Figure (6-4); it can be seen that the value of the cost for the insurer is close to zero. This is expected because the insurer is non-profit. The figure shows that the optimal discount rate is $338 per house and about 64% of homeowners will upgrade their house (36% will not upgrade). These results are also shown in Table (6-2).

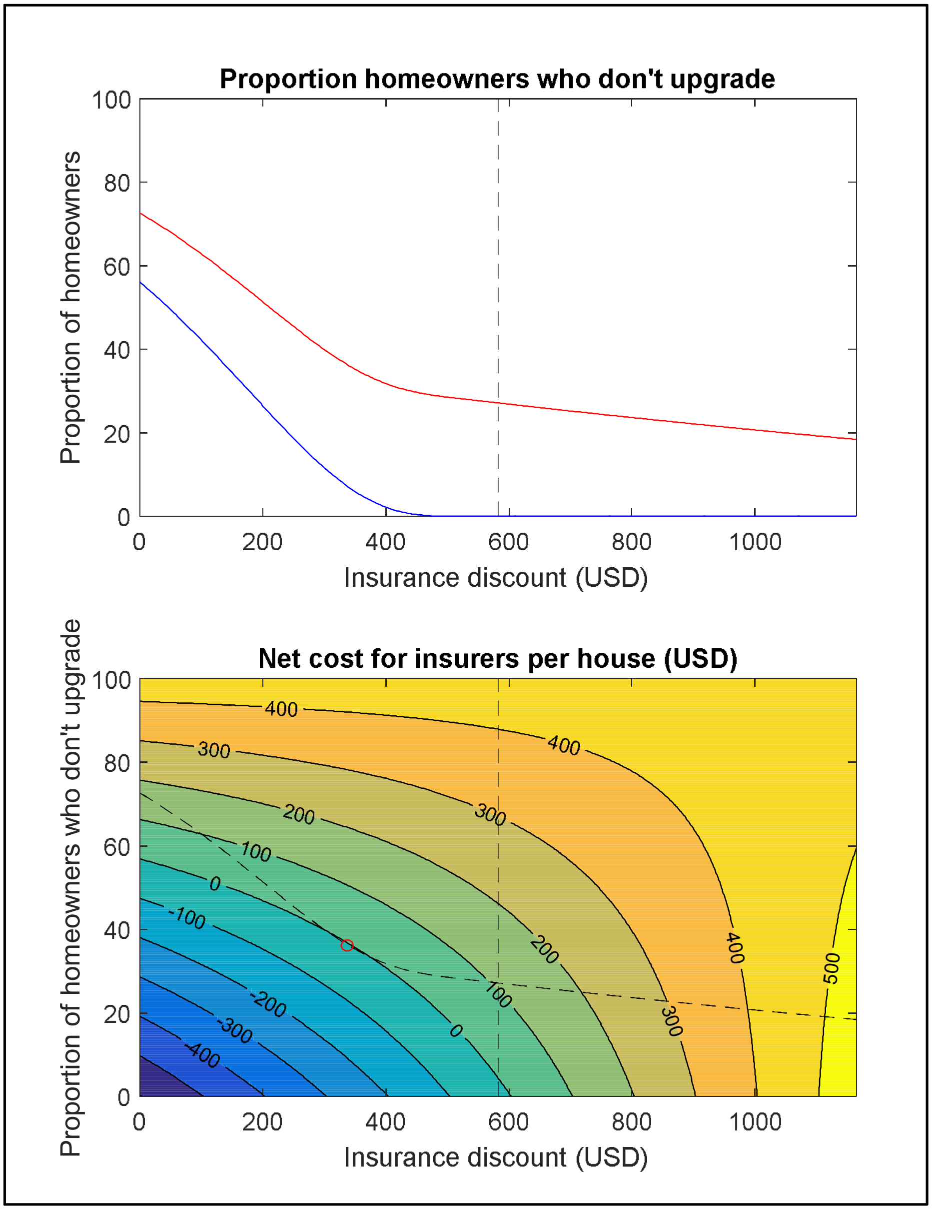

Fig. (6-4): Indifference curve and contour plot of the insurer's costs for the baseline case.

As mentioned earlier, the levels for the contour plot are calculated from equation (5-15):

$$\text{Loss} \quad = ER_{upgrade} * P_{upgrade} + ER_{no\ upgrade} * P_{no\ upgrade} - fee + discount * P_{upgrade}$$

With a few simple steps, we can find the slope of these contour lines. For convenience, we define:

X = insurance discount

Y = proportion of homeowners who don't upgrade ($P_{\text{no upgrade}}$)

I_{fee} = insurance premium fee

I_{cost} = cost for the insurer (loss)

ΔC = difference in expected repair costs with and without upgrade

$= ER_{\text{upgrade}} - ER_{\text{no upgrade}}$

Then, according to equation (5-15), we have

$$I_{cost} = ER_{\text{upgrade}}(1 - Y) + ER_{\text{no upgrade}}\, Y - I_{fee} + X(1 - Y)$$

$$= ER_{\text{upgrade}} - Y(\Delta C + X) - I_{fee} + X \qquad (6\text{-}2)$$

Since each curve of the contour plot for the cost of the insurer corresponds to a constant value of I_{cost}, the derivative of the last equation must be zero. Hence, to find the slopes of the contour lines, we solve the equation below:

$$dI_{cost} / dX = 0 = -dY / dX\,(\Delta C + X) - Y + 1 = 0$$

The final result for the slopes of the contour lines for insurer cost is obtained by solving for dY / dX:

$$dY / dX = (1 - Y) / (\Delta C + X)$$

One immediate conclusion of this result is that the contour lines for the insurer's cost will be vertical when:

$$X = -\Delta C \tag{6-3}$$

This is where the cost to the insurer due to the discount (X) equals the amount of saving due to the reduced cost of repair of an upgraded home (ΔC). This is illustrated in Figure (6-4) and the results in Table (6-2). The annual reduced cost of repair is

$$\Delta C = ER_{upgrade} - ER_{no\ upgrade} = \$217 - \$1279 = -\$1062$$

The corresponding discount in equation (6-3) is $X = -\Delta C = \$1062$, which is where the contours become vertical in Figure (6-4). This exercise demonstrates some of the potential uses of the analytical results that are associated with computational ABM.

In Figure (6-5) we show some of the intermediate results of the ABM, in which the horizontal axis show a range of possible values for the insurance premium (as given in the top row of Table 6-1) and the vertical axis is the net profit associated with each value of the premium. In determining the net profit, we use an analysis that is similar to that shown in Figure (6-4); the only difference is that the contour corresponding to the point of tangency is not necessarily associated with zero insurer cost. The value of this contour can be positive (net loss) or negative (net profit), and these values are plotted in Figure (6-5). As expected, the insurer's profit increases with an increase in the premium rates. The relationship is surprisingly linear, considering the nonlinear characteristics of the problem that can be seen in Figure (6-4). The value of the insurance premium that leads to a profit close to zero is \$821/year, as indicated by the circle in Figure (6-5) and shown in Table (6-2).

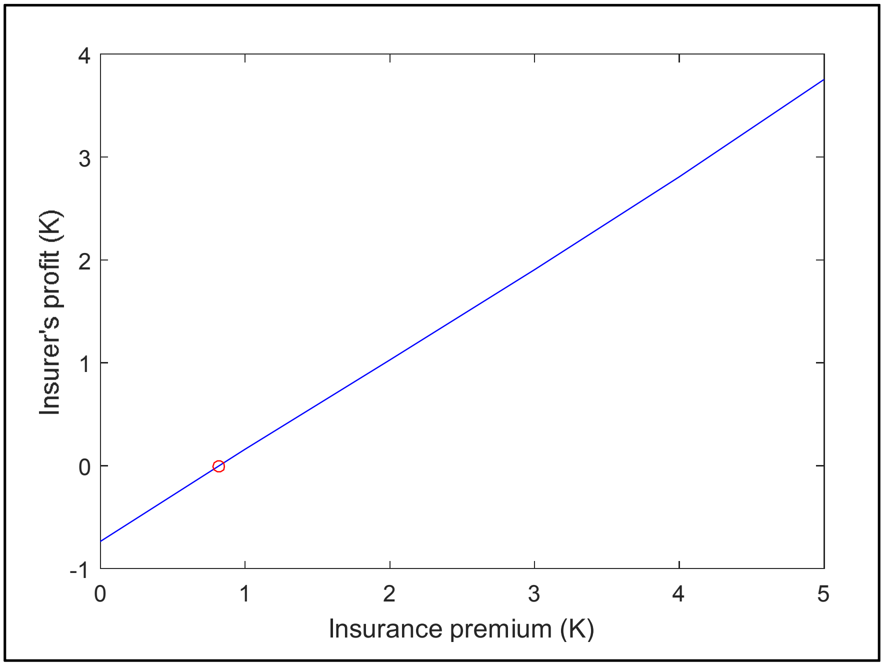

Fig. (6-5): Relationship between insurer profit and premium, with optimal insurance premium rate leading to no profit or loss indicated by the red circle.

The time series of the cumulative costs, revenue and change in reserves for the insurer are plotted in Figure (6-6). As noted in the previous chapter, this time series is not needed to determine any of the ABM results in Table (6-2), but are shown simply to indicate the randomness inherent in the theory. The top plot shows the reserve of the insurer per household, assuming that the insurer begins with zero reserves at time zero. For illustrative purposes only, the results are shown over a time period of 100 years. The middle plot is the cumulative amount of insurance premiums collected per household, and the bottom plot is the cumulative costs of repair per household. These plots have been calculated by taking the average of 120 iterations of the ABM. In the limit, as the number of iterations increases, the cumulative premium would equal to the cumulative cost and the result for the reserve would converge to zero.

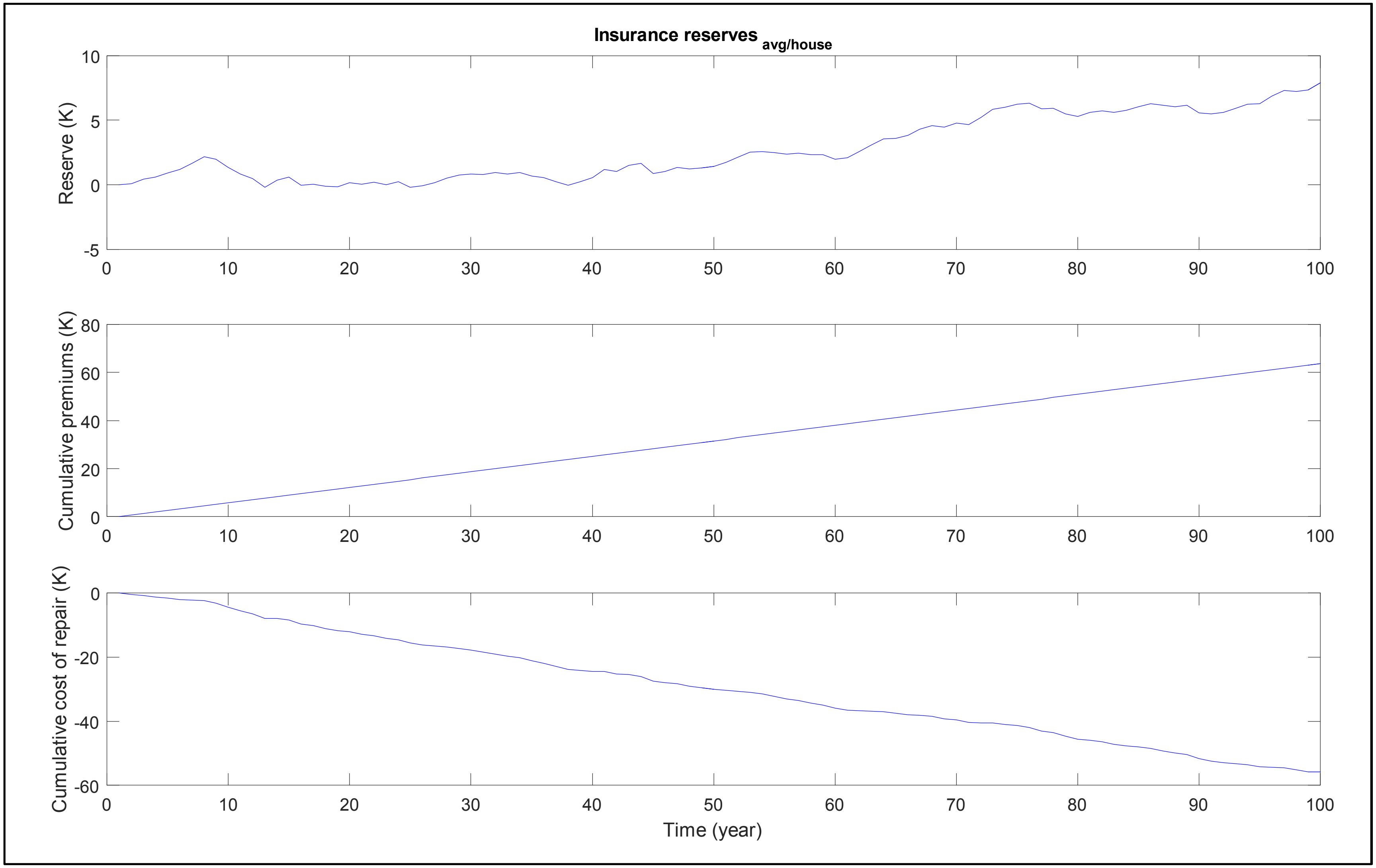

Fig. (6-6): Average time series of the reserve, cumulative premium and cumulative costs for the insurer per household.

6.3 Baseline with community measure

Here, we consider a 100-year flood protection measure for our example community. The properties of damage for upgraded and not upgraded houses are updated after the addition of the measure to reflect the smaller risk of flooding associated with the protective features of the measure. The affordability of the homeowners to upgrade is impacted because of the addition of the yearly cost of the measure.

Table (6-3) shows a summary of the model results for the baseline case after the addition of the flood control measure. By comparing these results with the corresponding results in Table (6-2) for a community without the measure, it can be seen that the measure significantly decreases the average costs of suffering and repairs. This is expected, given that the flood control measure decreases the probabilities of damage.

Table (6-3): ABM results for the baseline case with community measure.

Description	**Values**
$ES_{no\ upgrade}$	\$415/year
$ES_{upgrade}$	\$71/year
$ER_{no\ upgrade}$	\$463/year
$ER_{upgrade}$	\$79/year
Rational discount rate	\$1200
Optimal annual insurance premium rate	\$446
Optimal annual discount	\$95
Homeowners' expected annual cost per house	\$1962
Proportion of homeowners who don't upgrade	94%

The optimal insurance premium, optimal discount rate, average expected annual cost for the homeowners, and the rational discount rates are also lower in the community with the measure. One important difference between the two cases is that the proportion of homeowners that upgrade was reduced from 64% to only 6% for the community with the measure. This is because the houses are being protected against the risk of flooding by the flood control measure, and the rational discount rate is much higher in a community with a measure. The rational discount rate is the critical value for the rate of insurance premiums discounts, above which it is financially justified for homeowners to upgrade their property (equation 5-9), and with a higher rational discount rate, there will be fewer homeowners who will need to upgrade.

The affordability of the residents to upgrade will decrease due to the additional fee associated with the cost of the measure that has been added to the total annual costs for each homeowner. Figure (6-7) shows the decrease of affordability of the homeowners in the community with the measure, as compared with the corresponding plot in Figure (6-3) for the community without the measure.

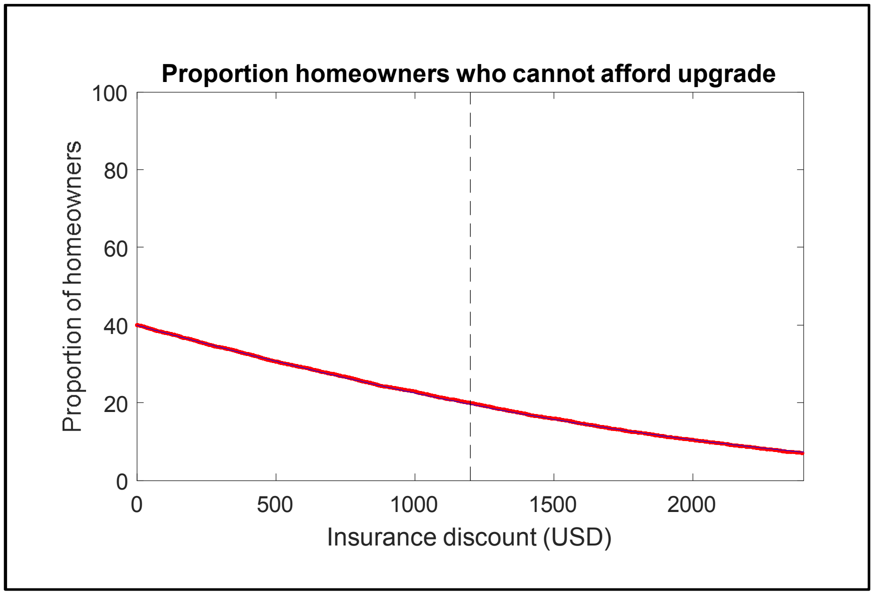

Fig. (6-7): Proportion of homeowners who cannot afford to upgrade as a function of the insurance discount in a community with the measure.

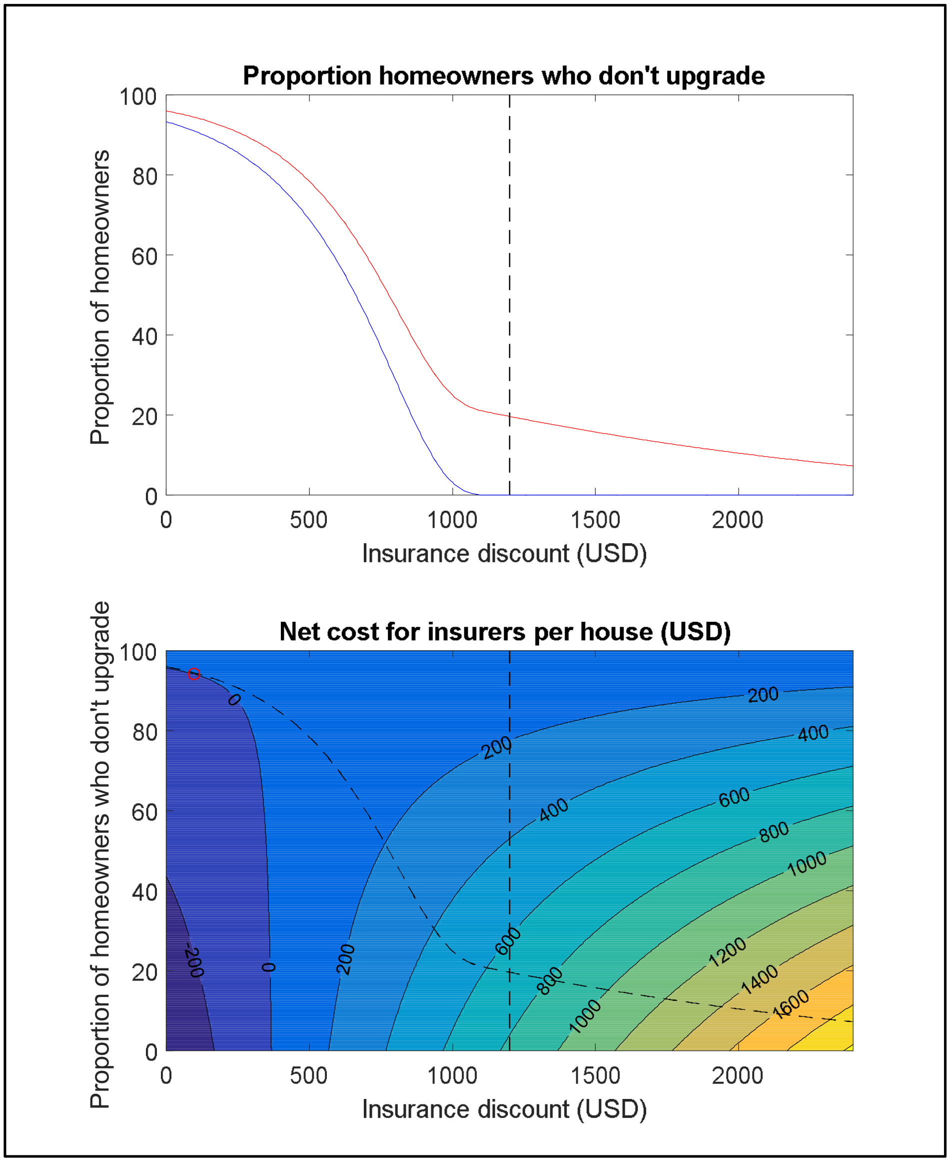

Fig. (6-8): Indifference curve and contour plot of the insurer's costs for the baseline case with community measure.

By comparing Figures (6-4) and (6-8), it can be seen how the indifference curve is lowered and how the majority of homeowners do not upgrade their houses after adding a measure to the community.

Next, we take a closer look at the effects of adding a measure to the community by plotting the ABM results with respect to an artificially parameter which we call "measure amount." Here, we are interested to see how the proportion of upgrades and other characteristics of the community change as we gradually add the protective effects and costs associated with the measure to the community. The measure amount ranges from zero (no measure) to one (measure). This is essentially a thought experiment of adding a measure gradually to the community, with cost and changes in probability of damage varying linearly with respect to this measure amount parameter. A subset of the ABM results are plotted with respect to this parameter in Figures (6-9) to (6-11).

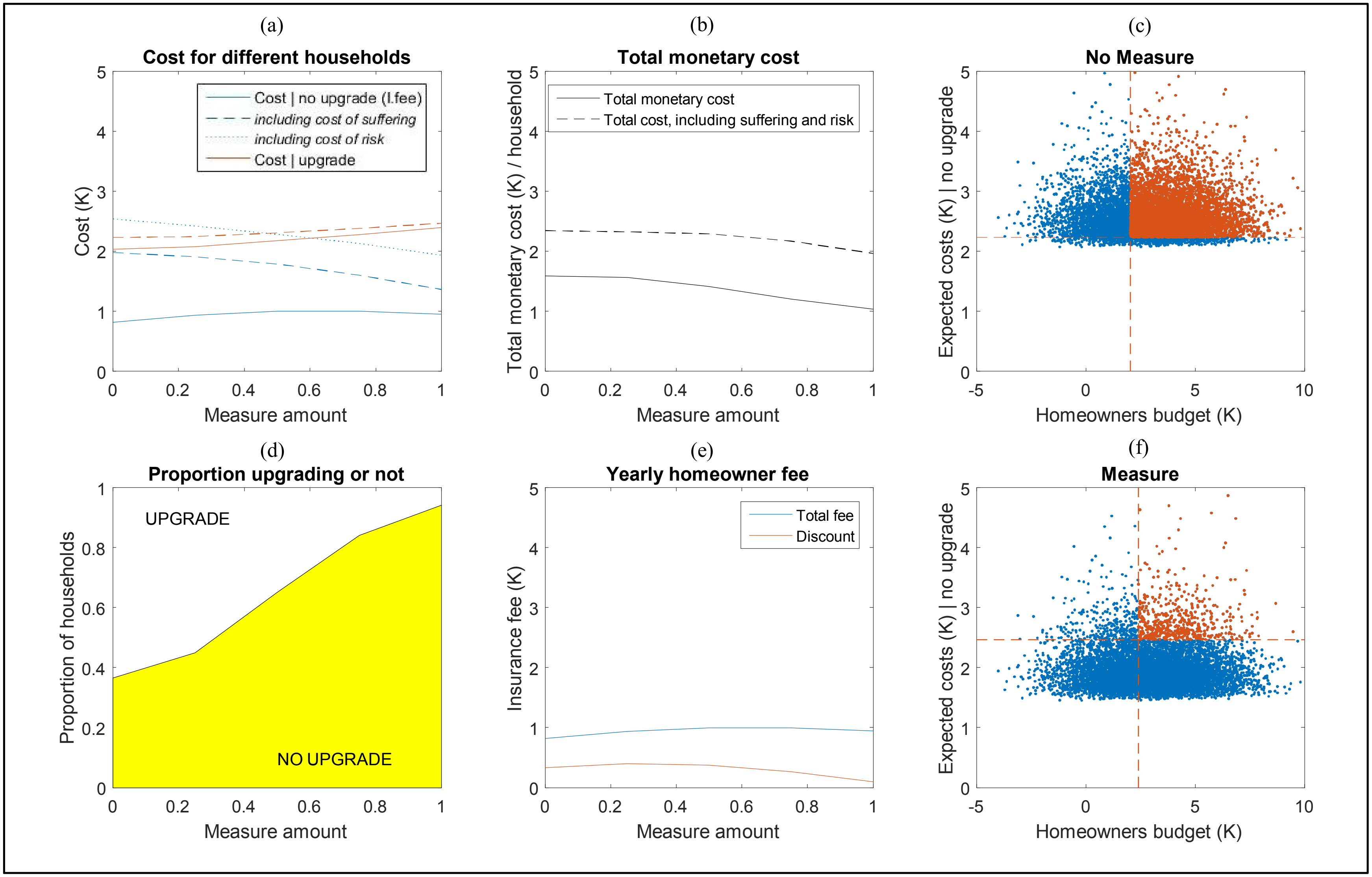

Fig. (6-9): ABM results for a variable measure (baseline case); K = 1000 USD per household.

Figure (6-9-a) shows how the average annual costs for the homeowners are influenced by the measure. The solid red line is for monetary costs associated with upgraded properties; it includes the discounted insurance premiums, the cost of the measure fee, prorated by the measure amount, and the cost of upgrade. In the red dashed line, we also include the cost of suffering. The solid and dashed blue lines show similar results for properties that are not upgraded, in which there are no discounts and no cost of upgrade. In the dotted blue line, we also include the cost of risk that, as noted in Chapter 5, is associated only with households who do not upgrade. The total costs are higher for upgraded houses because of the cost of upgrade. The no upgrade houses, however, have a much higher expected cost of suffering because of a higher probability of damage, regardless of the measure amount. Increasing the measure amount, however, will decrease the expected costs of suffering for both upgraded and not upgraded properties. This drop in the cost of suffering is greater in the no upgrade case since the upgraded properties have a substantial level of protection even without a measure.

In Figure (6-9-b), we show the average total costs of a community as a whole versus the measure amount. In the solid curve, we show only the total monetary costs, which consists of the prorated cost of the measure, average cost of upgrading houses, and average cost of repair. This cost decreases as the measure amount increases because of lower probabilities of damage and reduced proportion of upgrades. In the dashed curve, we include the average costs of risk and suffering. This result also decreases with the increase of measure, but this is primarily due to the reduced monetary costs.

Figure (6-9-d) shows the proportion of upgraded and not upgraded houses for different values of the measure amount. As the measure amount increases, a higher proportion of households will upgrade; this is consistent with model results in Tables (6-2) and (6-3).

Figure (6-9-e) shows the average of the annual fees for the homeowners along with the average discount, plotted versus the measure amount. The results show that the average fee increases with the measure amount. This is because the cost associated with the measure does not entirely offset the savings due to reduced probability of damage. There is also the decrease in the number of upgraded houses, shown in Figure (6-9-d) that counteracts this reduced probability of damage.

In Figure (6-9-c), we plot a scattergram of the total expected costs for each of the 9000 homeowners. The vertical axis shows this cost before an upgrade ($EC_{no\ upgrade}$) and the horizontal axis shows the homeowner's budget. The vertical dashed line is the total yearly cost associated with the upgrade; hence, only those homeowners with budgets that are above this cost, indicated by the dots to the right of the line, can afford an upgrade. Out of these households who can afford the upgrade, only those who would pay higher costs if they did not upgrade would opt for the upgrade. The horizontal dashed line is the common yearly expected cost of any upgraded household ($EC_{upgrade}$); households with higher costs without the upgrade, indicated by the dots above this line, would prefer to upgrade. Taking affordability and expected cost together, the subset of households who would upgrade would correspond to those points that are to the right of and above the two dashed lines. These points are shown in red.

Figure (6-9-f) is a similar plot, and the results differ from the plot above in Figure (6-9-c) in that the community has a protective measure. Here there are fewer dots on the right side of the vertical line compared to Figure (6-9-c). This is because the affordability of the homeowners decreases after adding a measure to the community, as the residents will have an additional annual fee associated with the cost of the measure. Although the total expected cost for the homeowners in Figure (6-9-f) is lower compared to the community with no measure, because of a smaller probability of damage, a greater number of the dots fall below the horizontal line where it is more financially reasonable for them not to upgrade. This leads to a smaller number of red dots compared to Figure (6-9-c), which means when there is a measure in the community, a smaller proportion of the homeowners will ultimately upgrade. This is also consistent with the model outputs in Tables (6-2) and (6-3).

Figure (6-10) shows a series of scattergrams of utilities of each of the 9,000 homeowners. The coordinates of each point are: (U_i, U'_i) = (utility of homeowner i for the community without a measure, utility of homeowner i for the community with the measure), in which the utilities are determined by equation (5-16). The exponent x_i, representing the degree of interest of homeowner i in supporting the community and is assumed to be the same for all homeowners, $x_i = x$. The special case where the utilities are equal, where the homeowners are indifferent with respect to the existence or non-existence of a measure, is indicated by the diagonal red line. Figure (6-10-a) is for the case where the exponent $x = 0$. Here, the utilities reduce to those of the homeowners as individuals in the community, $(U_i, U'_i) = (U_{i,\text{individual}}, U'_{i,\text{individual}})$, which are computed using equation (5-17). Figure (6-10-d) is the same plot but with jitter to aid in visualizing the density and number of points. The blue dots are for homeowners who never upgrade, while the yellow dots are for those who always upgrade. The red dots are the properties that do not upgrade if there is a measure, but will upgrade if the measure is not built. The average utilities of each of these three group of homeowners is marked with a circle of the same color, and the average of all three groups is marked with a plus sign (+).

The scattergrams in Figures (6-10-a) and (6-10-d) can be compared with those in Figures (6-10-c) and (6-10-f), which correspond to the case where the exponent $x = 1$. Here, the utilities become $(U_i, U'_i) = (U_{\text{community}}, U'_{\text{community}})$, representing homeowners whose utilities are given by the average utilities of all of the members of the community, as given by equation (5-19). It can be seen that all of the points in the scattergram end up at a single point in Figure (6-10-c) and in a small cloud of points, because of the jitter, in Figure (6-10-f). It is noted that in Figure (6-10-c), the points are at the same location as the average utility represented by the plus sign, as expected. For other values of the exponent x, the points of the scattergrams would lie between these two extreme cases. This can be seen in Figures (6-10-b) and (6-10-e), which show the intermediate case, $x = 1/2$.

In each of these scatterplots, when the data points falls above the diagonal line, then the utilities of the corresponding homeowners is higher after adding a measure to the community, otherwise the utilities are lower. The ABM results for the baseline case, as plotted in Figure (6-10), indicates that the average utilities of all the residents is higher after building a measure because the plus symbol falls above the diagonal line. This is also true for most of the individual homeowners for $x = 0$ and 1/2. In the next sections, we show the scattergram results of other cases to examine the placement of the utility points with respect to the indifference diagonal line.

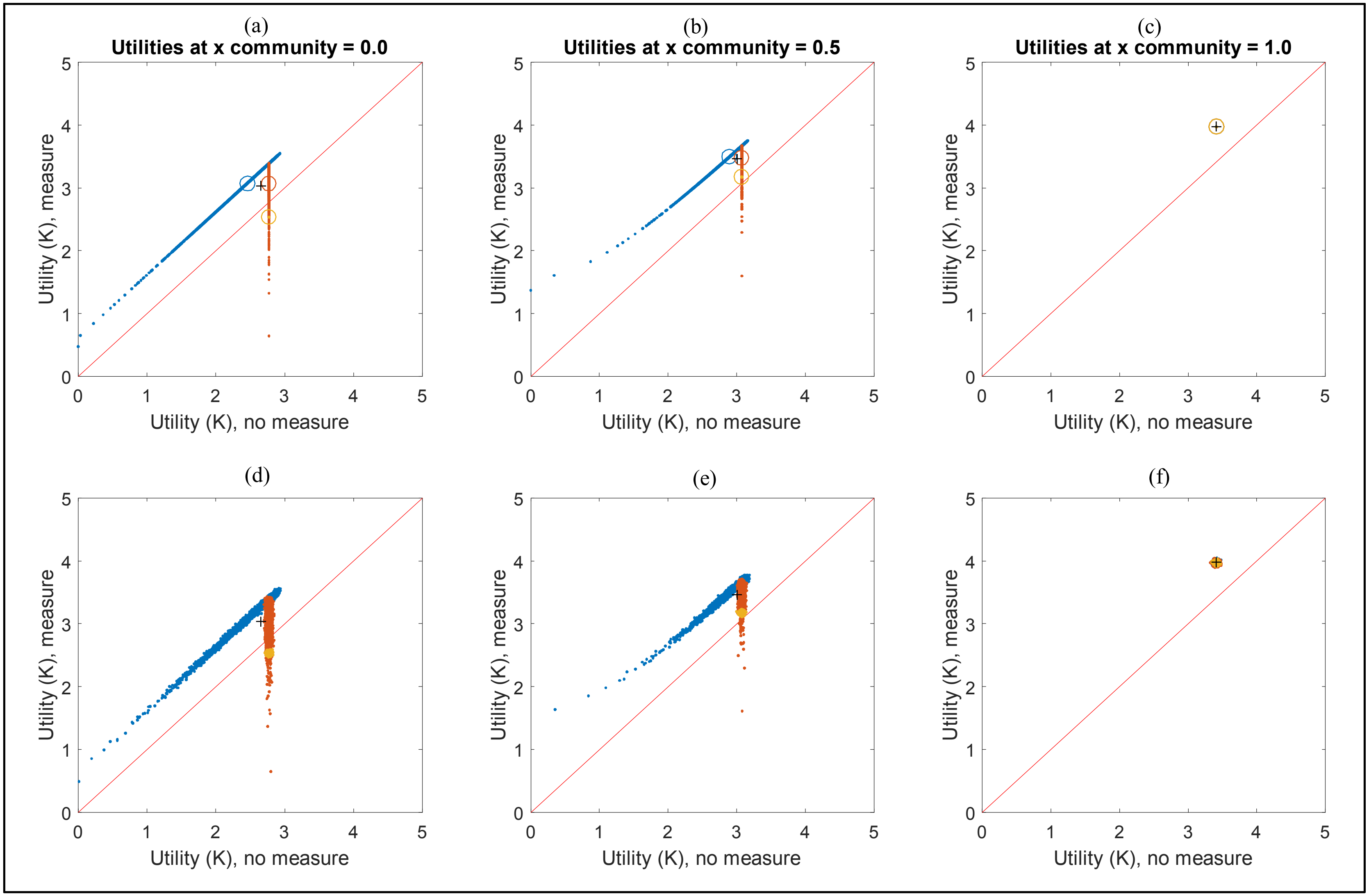

Fig. (6-10): Available resource for each household in a community (baseline conditions).

Figure (6-11) illustrates average of total utilities in a community before and after adding a measure for the baseline conditions versus the utility exponent *x* that represents the degree of community interest. We use the term “X community” for this exponent.

The blue and red curves are the average utilities before and after a protective measure is added to the community, plotted with respect to the exponent x. In Figure (6-11), the red curve always falls above the blue curve, which indicates that for the baseline case, it is of greater utility to add the measure to the community regardless of the degree of interest in the community, *x*, of the residents of the community.

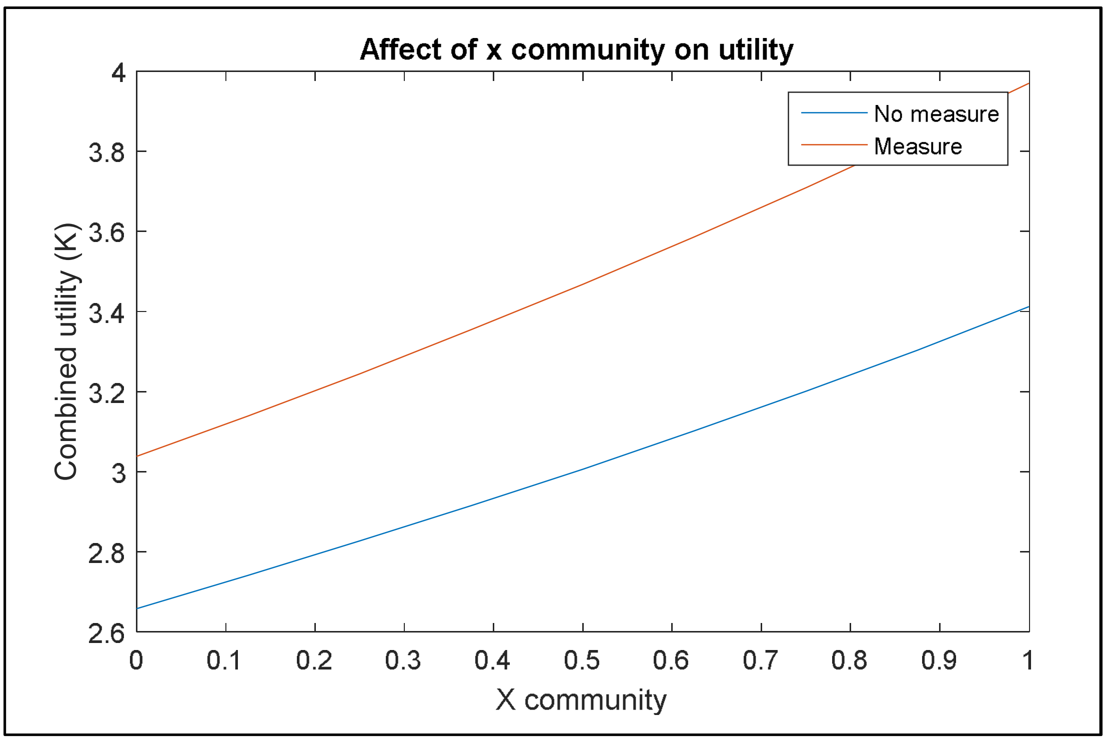

Fig. (6-11): Average community utilities before and after adding a measure (baseline conditions).

6.4 Less Costly Property Upgrades

In this section, we have decreased the average cost of individual house upgrades by 30% compared to the baseline conditions to see whether a smaller cost of upgrade would encourage more upgrades in the community; and, to study how it affects the total utilities in the community. Table (6-4) includes the summary of ABM outputs for this scenario.

Comparing this scenario with the baseline conditions (including the flood control measure), shows that a higher proportion of homeowners will upgrade when the cost to upgrade is smaller. The rational discount rate is also smaller than the baseline conditions while the value of optimal insurance premiums and the optimal discount rates remain close to the baseline conditions.

Table (6-4): Summary of ABM output for less costly house upgrades.

Description	Values
$ES_{no\ upgrade}$	$415/year
$ES_{upgrade}$	$71/year
$ER_{no\ upgrade}$	$463/year
$ER_{upgrade}$	$79/year
Rational discount rate	$736
Optimal annual insurance premium rate	$378
Optimal annual discount	$74
Homeowners’ expected annual cost per house	$1836
Proportion of homeowners who don’t upgrade	75%

ABM output plots in Figure (6-12) also show how a higher proportion of the population can afford an upgrade, and will thus upgrade their properties in this scenario.

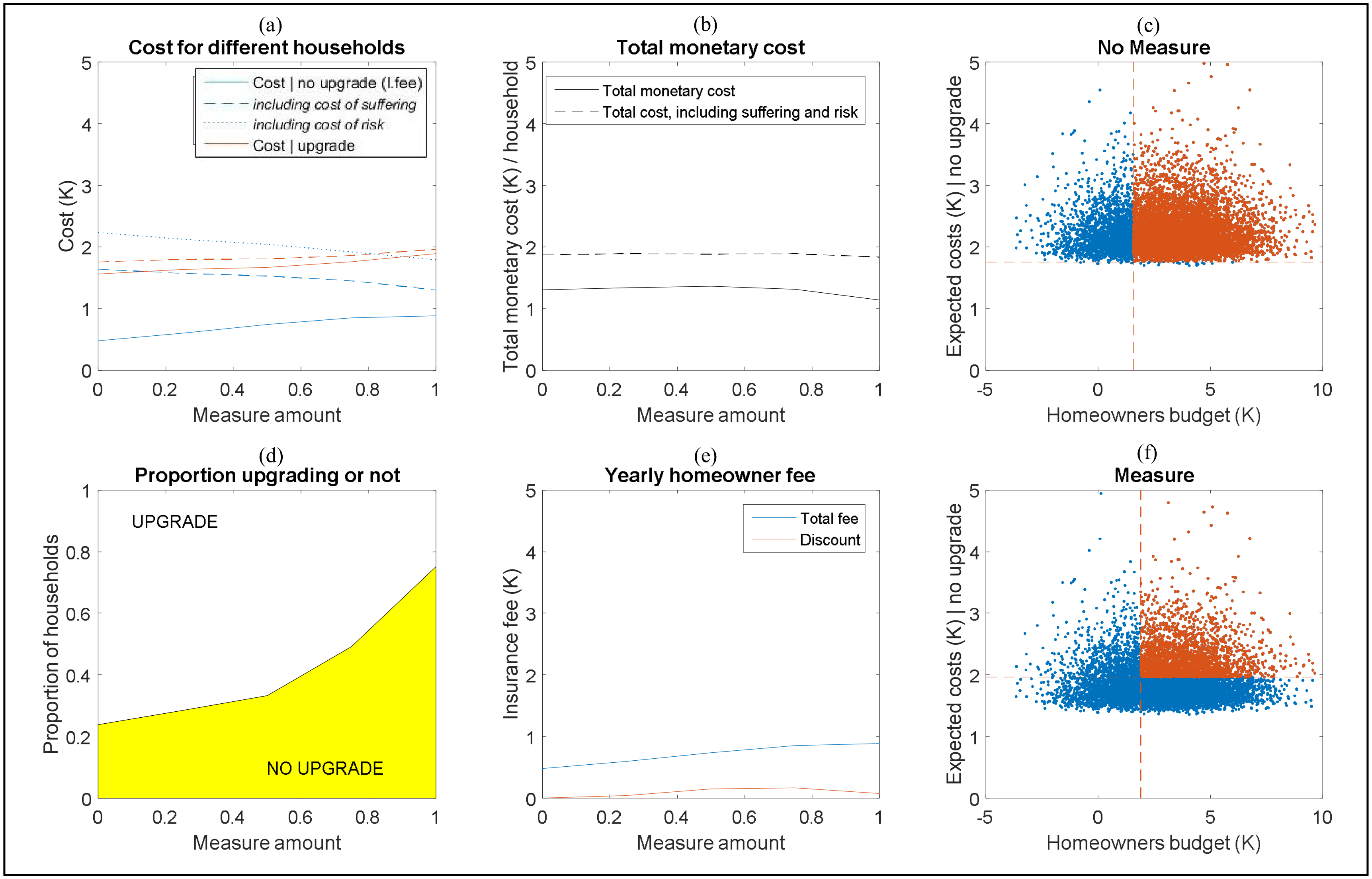

Fig. (6-12): ABM results for a variable measure (less costly property upgrades).

Figures (6-13) and (6-14) show how the utilities change from the baseline conditions for this scenario. Comparing the plots of Figures (6-13) and (6-10) indicated that when the cost of upgrade is lower, the average utilities (plus sign in the Figures) is lower than the baseline conditions, but still falls above the diagonal line in all six subplots.

This means that even after reducing the cost of upgrades for the homeowners, the average utilities for individual homeowners and the entire community are higher when there is a measure intact; and therefore, it is still worthwhile to build a measure.

Average utilities of the homeowners are lower in this scenario because a higher proportion of the homeowners upgrade their properties when the cost of upgrade is lower than the baseline conditions, and therefore, the cost of upgrade is added to their total annual costs.

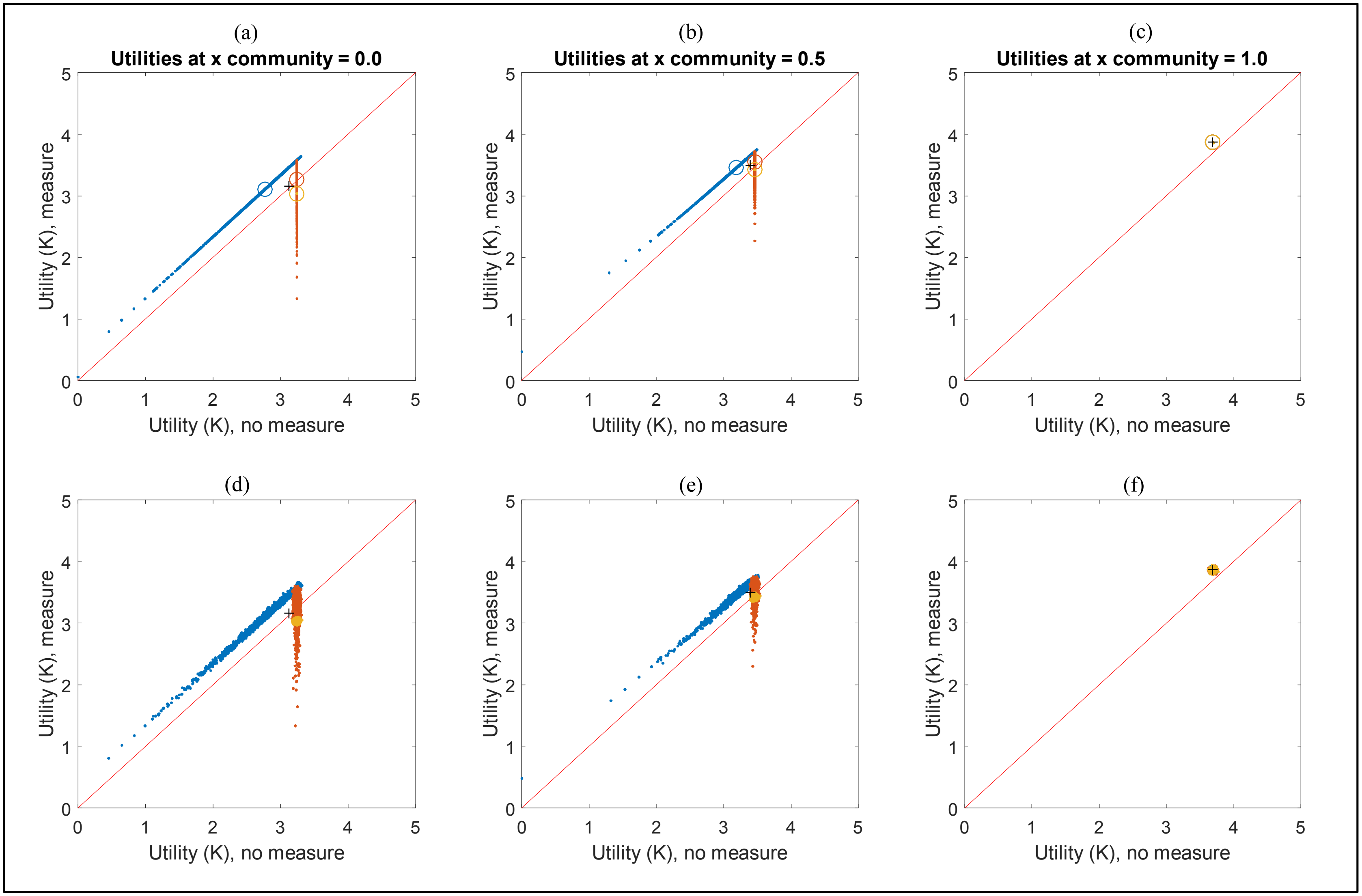

Fig. (6-13): Available resource for each household in a community (less costly property upgrades).

Although the gap between the red and blue curves of Figure (6-14) is smaller than Figure (6-11), the red curve (measure intact) still falls above the blue curve (no measure) for all values of X community, which indicates the combined utilities are higher when there is a measure intact.

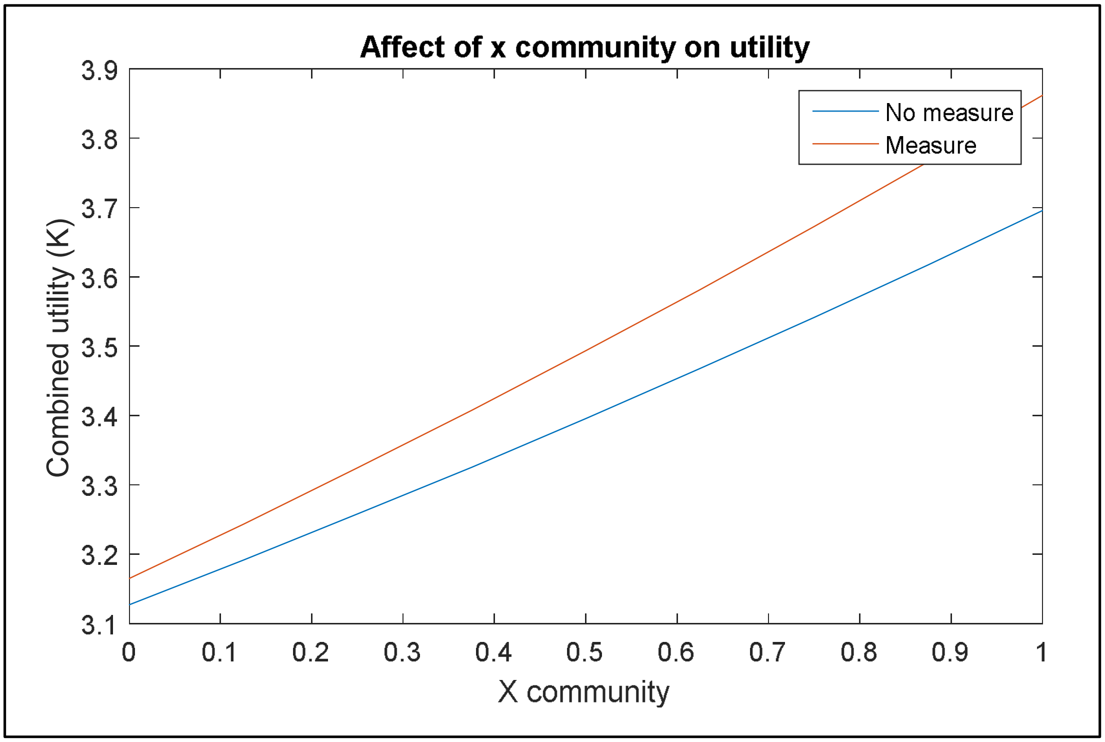

Fig. (6-14): Average community utilities before and after adding a measure (less costly property upgrades).

6.5 Less Costly and More Effective Property Upgrades

In this section, compared to the baseline conditions, we have decreased the costs of an upgrade for the homeowners by 30% and also increased the effect of an upgrade by 40% (40% smaller probability of damage for each storm) to see whether a more effective, less costly upgrade would encourage more upgrades in the community and/or how it affects the total utilities in the community. Table (6-5) includes the summary of ABM outputs for this scenario.

As expected, even more people will upgrade their properties in this scenario compared with the previous scenario and the baseline conditions. The rational discount rate is slightly lower compared to the previous scenario and the average total annual costs for the homeowners are also slightly lower.

Table (6-5): Summary of ABM output for more effective and less costly house upgrades.

Description	Values
$ES_{\text{no upgrade}}$	\$415/year
ES_{upgrade}	\$28/year
$ER_{\text{no upgrade}}$	\$463/year
ER_{upgrade}	\$32/year
Rational discount rate	\$694
Optimal annual insurance premium rate	\$362
Optimal annual discount	\$110
Homeowners' expected annual cost per house	\$1793
Proportion of homeowners who don't upgrade	68%

ABM results are illustrated in Figures (6-15). Subplot (a) shows a higher proportion upgrading compared to the previous scenarios and subplot (c) shows how it is financially reasonable for almost all of the homeowners to upgrade before adding a measure, as almost all of the dots are above the horizontal line. Of course, a proportion of the homeowners on the left side of the vertical line will not be able to afford an upgrade and their properties remain not upgraded (the blue dots in Figure 6-15-c). After adding a measure, a smaller proportion of the homeowners will upgrade because their total expected costs will be lower after building the measure.

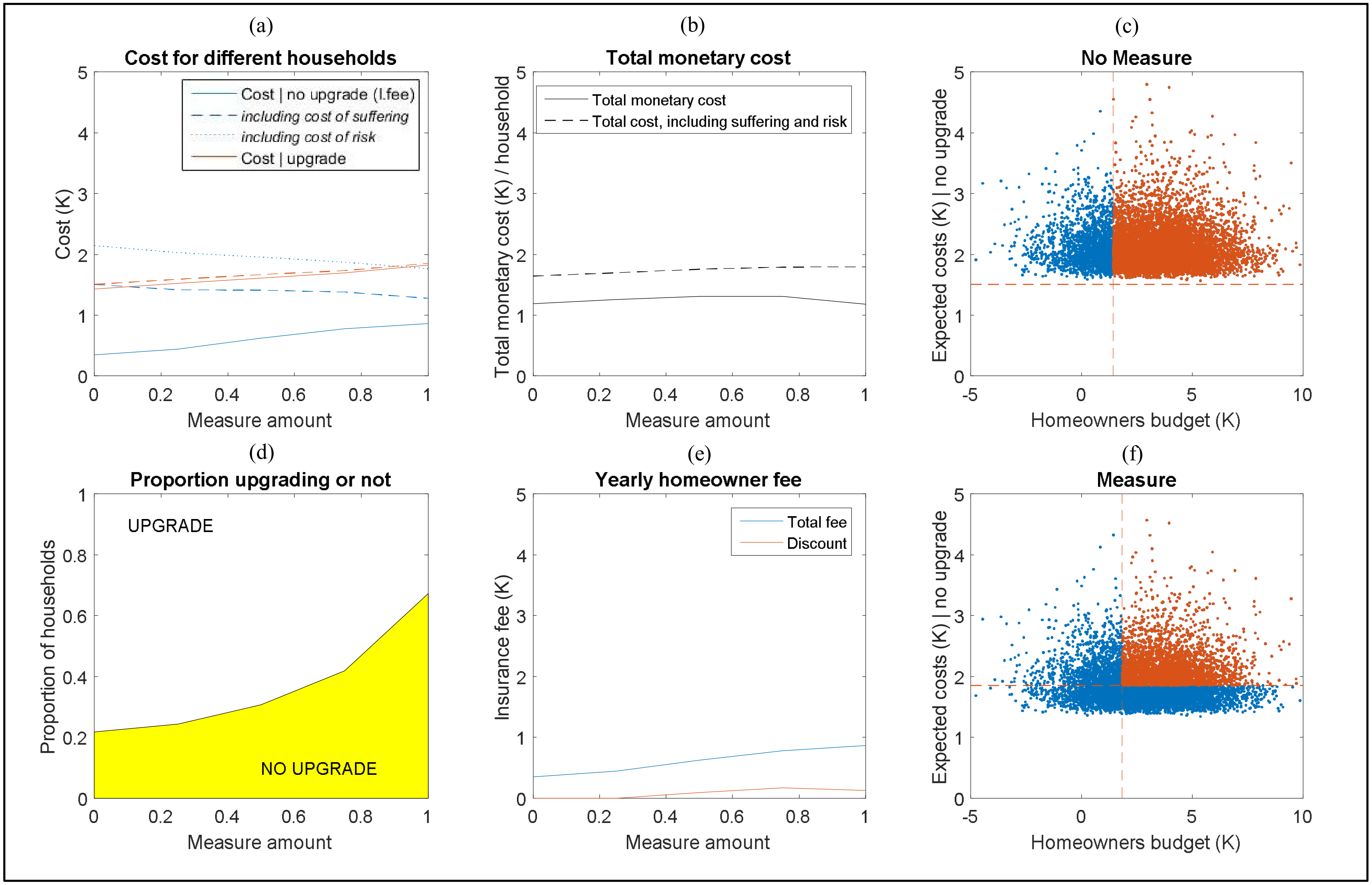

Fig. (6-15): ABM results for a variable measure (more effective and less costly property upgrades).

The plus sign that shows the average utilities in Figures (6-16) falls below the diagonal line in subplots (a), (b) and (d); in this scenario this means that the average utilities of the individual homeowners (X community = 0), and the average utilities of the homeowners plus the community (X community = 0.5) are higher before adding a measure to the community. The plus sign falls only slightly above the diagonal line in subplots (c) and (f), indicating that after reducing the cost of upgrades for the homeowners and adding the efficiency of the upgrades, the average utilities of the community (X community = 1) are still higher after adding a measure and, from the perspective of the community as a whole system, it is still worthwhile to build a measure.

If the residents of this community were to vote for or against building a measure, this would be an interesting scenario in which different agents of the system may have opposite opinions about whether or not a measure should be built. There are a group of homeowners whose average utilities are higher after adding a measure (blue dots in Figure 6-16). Other groups of homeowners would have higher average utilities before building a measure in the community (red and yellow dots). In scenarios like this, another important factor in the final decision towards building a measure would be the weight of the votes for different groups of residents. As an example, the number of residents in one group might be higher, but the opposite group might have higher influence on the ultimate decision making for the community. In our model, we have considered equal votes for all the residents. We also assume the only factor important to the voters is their expected utilities and monetary values in each scenario. In reality, there are other important factors involved in decision making towards building a measure to protect a community, such as adverse social and emotional effects of flooding that are not being modeled here.

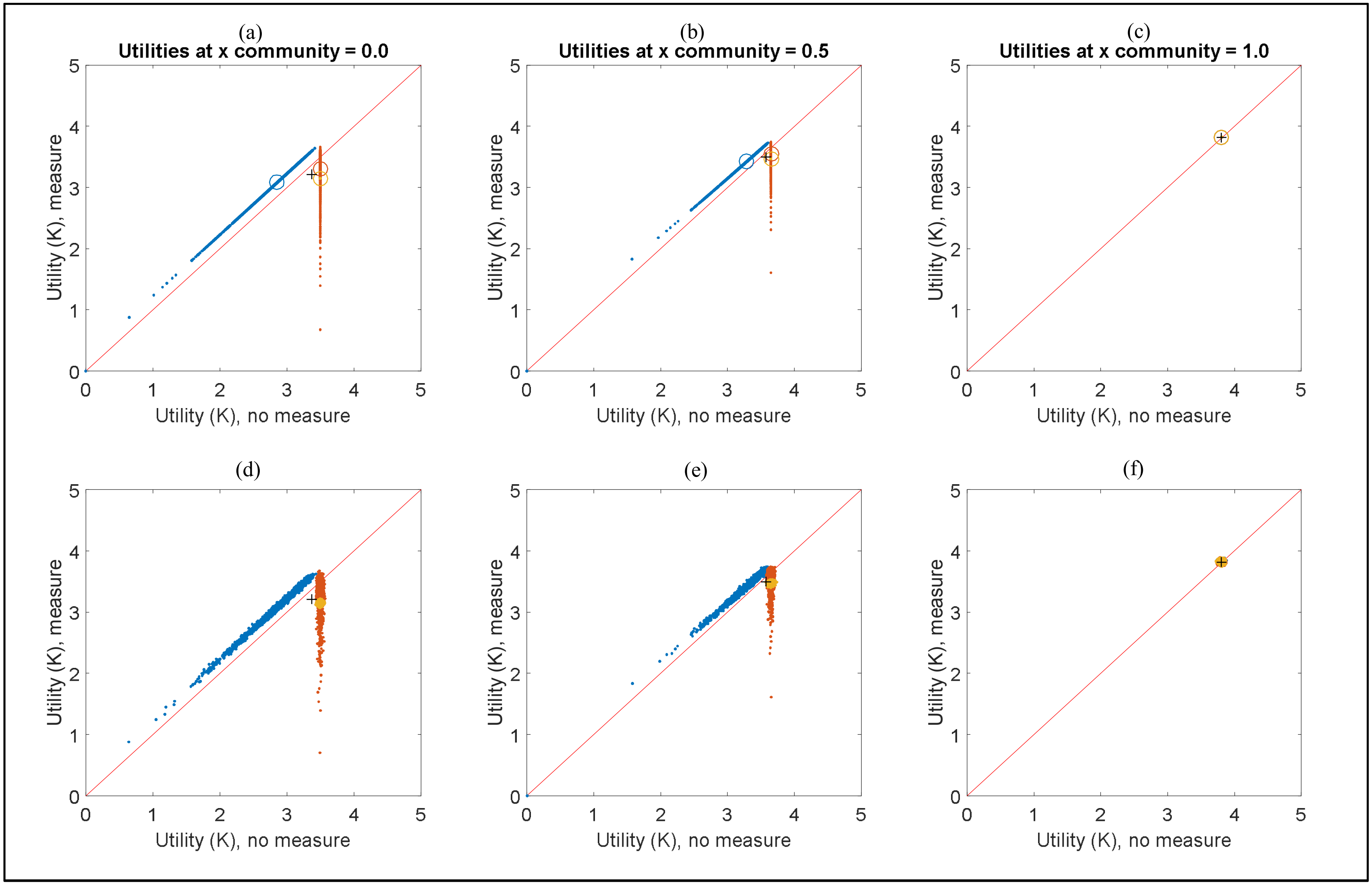

Fig. (6-16): Available resource for each household in a community (more effective and less costly property upgrades).

In Figure (6-17) the red and blue curves cross. The combined utilities of the homeowners (X community = 0) are higher before adding a measure (blue curve). The utilities of the community as a whole (X community = 1), however, are slightly higher after building a flood control measure (red curve).

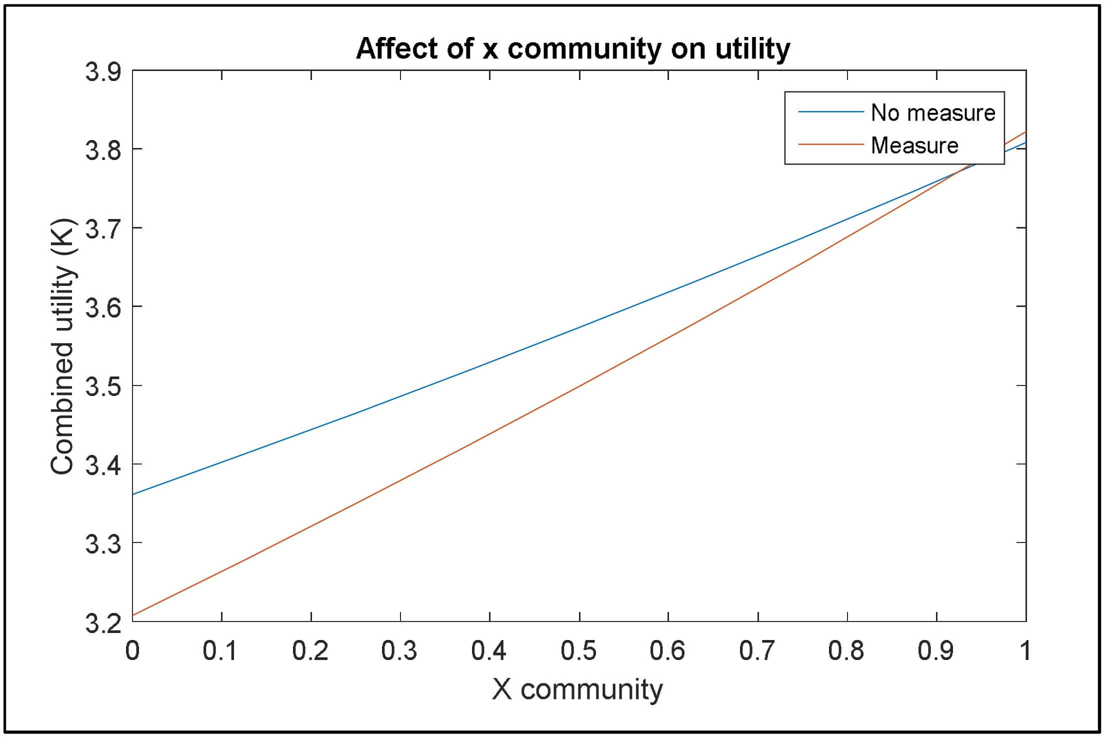

Fig. (6-17): Average community utilities before and after adding a measure (more effective and less costly property upgrades).

In the following section, we model a different scenario by changing the model controller parameters to see whether there is a situation in which everyone in the community would potentially vote against building a measure.

6.6 Less Costly and More Effective Property Upgrades Combined with Higher Cost of Measure

In this section, compared to the baseline conditions, we have decreased the cost of upgrade for the homeowners by 30%, increased the effect of upgrade by 40% (40% smaller probability of damage for each storm), and also increased the cost of measure by 100% (twice as expensive) to see whether this scenario leads to a different outcome, e.g. would it be more cost effective to upgrade the individual houses instead of building the flood control measure. In this scenario, increasing the cost of measure will not change the effectiveness of the measure. In other words, the more costly measure in this community provides the same level of protection as the previous scenarios. Table (6-6) includes the summary of ABM outputs for this scenario.

In this scenario, average homeowners' expected annual costs are higher compared to the previous scenario because building a more costly measure means higher taxes (measure fee) for the residents of the community. A smaller proportion of homeowners will upgrade their properties compared to the previous scenario because a fewer number of homeowners can afford an upgrade due to an increase in their annual costs. The optimal annual insurance premium rate and optimal discount rates remain similar to the previous scenario because the higher cost of measure will not directly affect the costs for the insurance company.

Table (6-6): Summary of ABM output for more effective and less costly house upgrades and more costly flood control measure.

Description	Values
$ES_{no\ upgrade}$	\$415/year
$ES_{upgrade}$	\$28/year
$ER_{no\ upgrade}$	\$463/year
$ER_{upgrade}$	\$32/year
Rational discount rate	\$694
Optimal annual insurance premium rate	\$374
Optimal annual discount	\$114
Homeowners' expected annual cost per house	\$2314
Proportion of homeowners who don't upgrade	72%

Figures (6-18) shows ABM results for this scenario. Subplot (d) shows that a higher proportion of homeowners will upgrade in this scenario. Subplots (a), (b), and (e) show the higher annual costs for homeowners after adding a measure. The blue dotted line in subplot (a) shows the average expected costs for homeowners who do not upgrade, including cost of suffering and cost of risk. This line is higher than the dashed red line (total expected cost for the homeowners who upgrade) before adding a measure (measure amount = 0), which means for all the residents, it is financially reasonable to upgrade. This can also be seen in subplots (c) where all the dots fall above the horizontal line. The blue dots on the left side of the vertical line will not be able to afford an upgrade. After building a measure (measure amount = 1) the dotted line in subplot (a) is very close to the red dashed line which indicates that after a measure is built, the total costs for the homeowners who upgrade are only slightly higher than those who do not upgrade. This can also be seen in subplot (f) in which a great number of dots fall above the horizontal line.

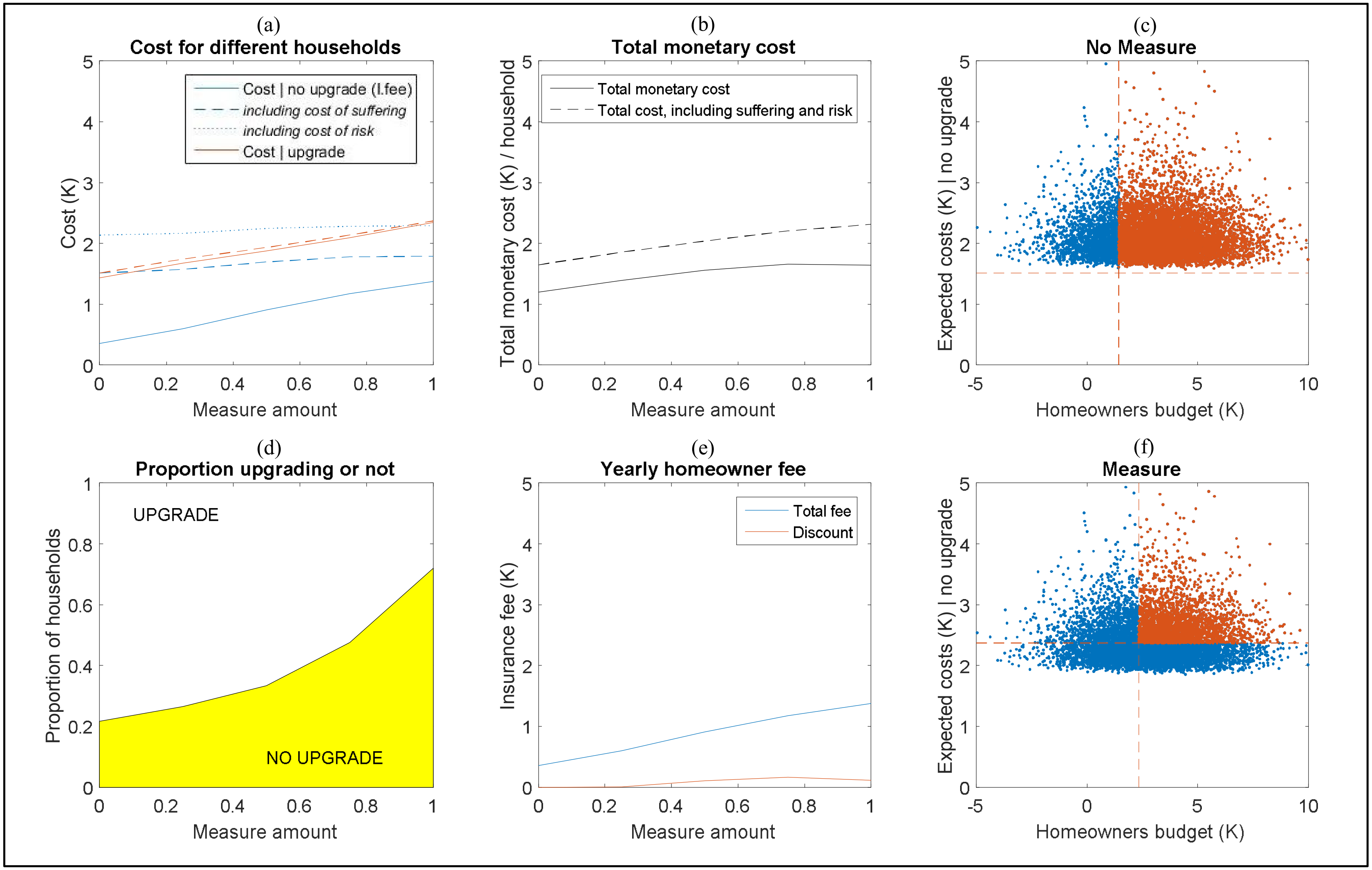

Fig. (6-18): ABM results for a variable measure (more effective and less costly property upgrades+ more costly measure).

The average utilities for all groups of the homeowners, and the community (plus sign and circles) fall below the diagonal line in all subplots of Figures (6-19). This indicates that after reducing the cost of upgrades for the homeowners, increasing the efficiency of the upgrades, and increasing the cost of measure, building a measure would not be cost effective and before building the measure, the average utilities would be higher for all homeowners and the community.

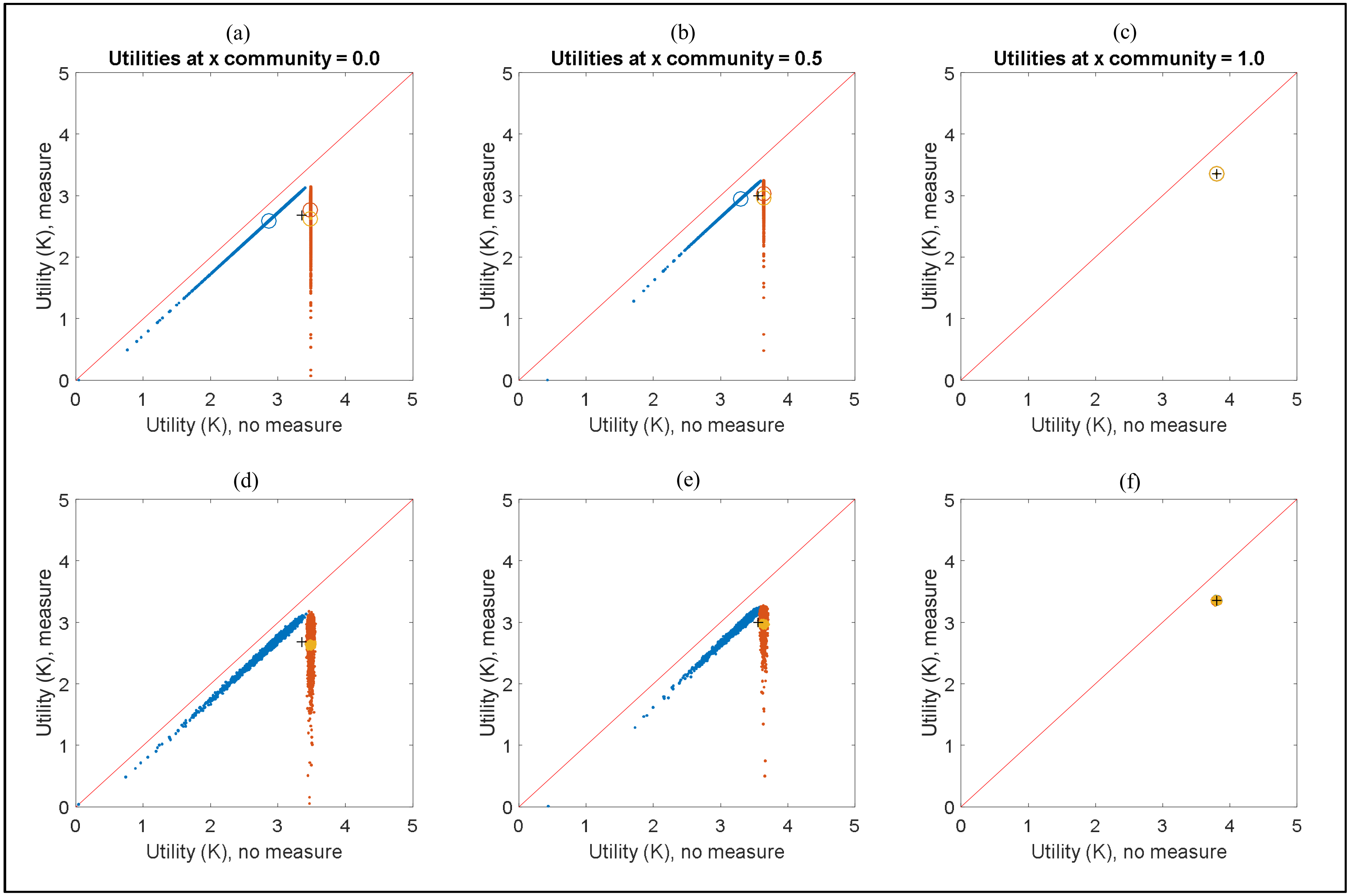

Fig. (6-19): Available resource for each household in a community (more effective and less costly property upgrades+ more costly measure).

Figure (6-20) shows that in this scenario, combined utilities for the homeowners (at X community = 0) and the community (at X community = 1) before adding the measure (blue curve) is much higher than it is after building a measure (red curve).

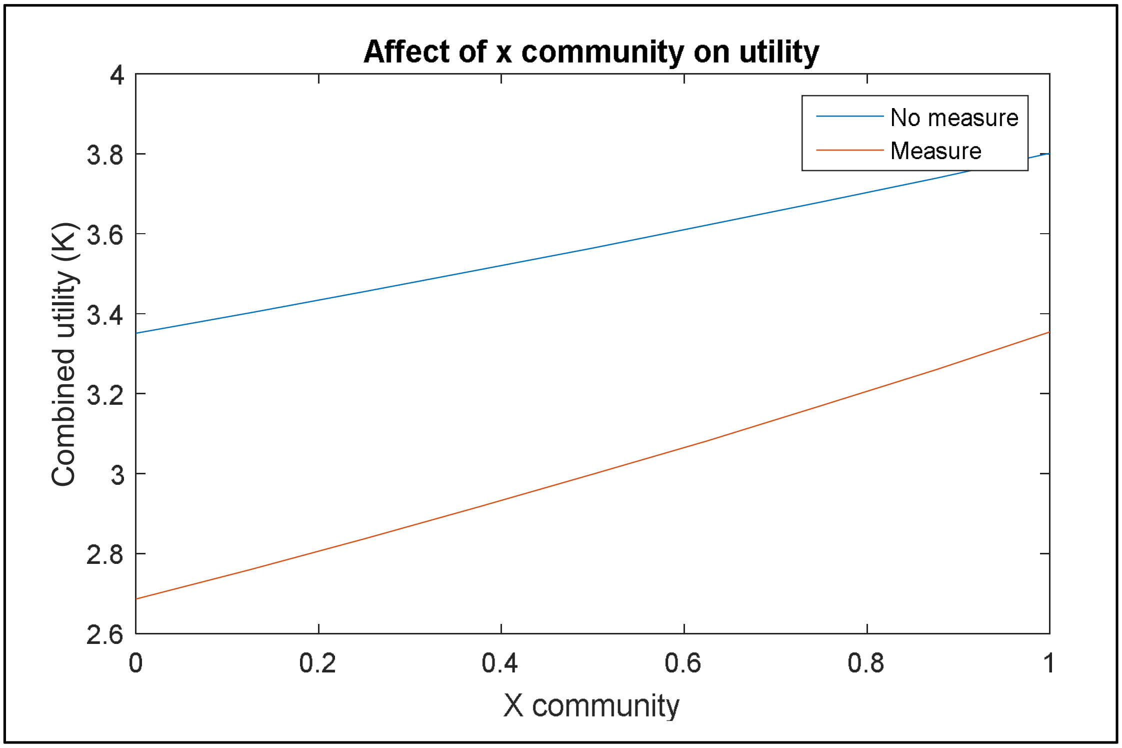

Fig. (6-20): Average community utilities before and after adding a measure (more effective and less costly property upgrades + more costly measure).

6.7 More Effective Measure

In this section, we have increased the measure efficiency by 100% (twice as effective) compared to the baseline conditions to study the effects of a stronger measure on the ABM results. To increase the measure efficiency we have decreased the probability of damage due to all possible storms for all properties by 50% compared to the baseline conditions shown in Table (6-1). The summary of ABM outputs for this scenario is presented in Table (6-7).

Table (6-7): Summary of ABM output for stronger measure.

Description	**Values**
$ES_{\text{no upgrade}}$	\$208/year
ES_{upgrade}	\$35/year
$ER_{\text{no upgrade}}$	\$232/year
ER_{upgrade}	\$39/year
Rational discount rate	\$1372
Optimal annual insurance premium rate	\$227
Optimal annual discount	\$0
Homeowners' expected annual cost per house	\$1548
Proportion of homeowners who don't upgrade	98%

Compared to the ABM outputs for the baseline conditions with a measure (Table 6-3), here we have much lower costs of suffering for upgraded or not upgraded houses due to a great reduction in the probability of damage. The rational discount rate is slightly higher in this case. Optimal insurance premiums are smaller in this case. A smaller proportion of the homeowners will upgrade. And the average of total annual expected costs of the homeowners is smaller when the measure is more effective due to a smaller number of upgrades. Figure (6-21) shows how adding a strong measure can benefit all the homeowners and the community as a whole by a great increase in the utilities.

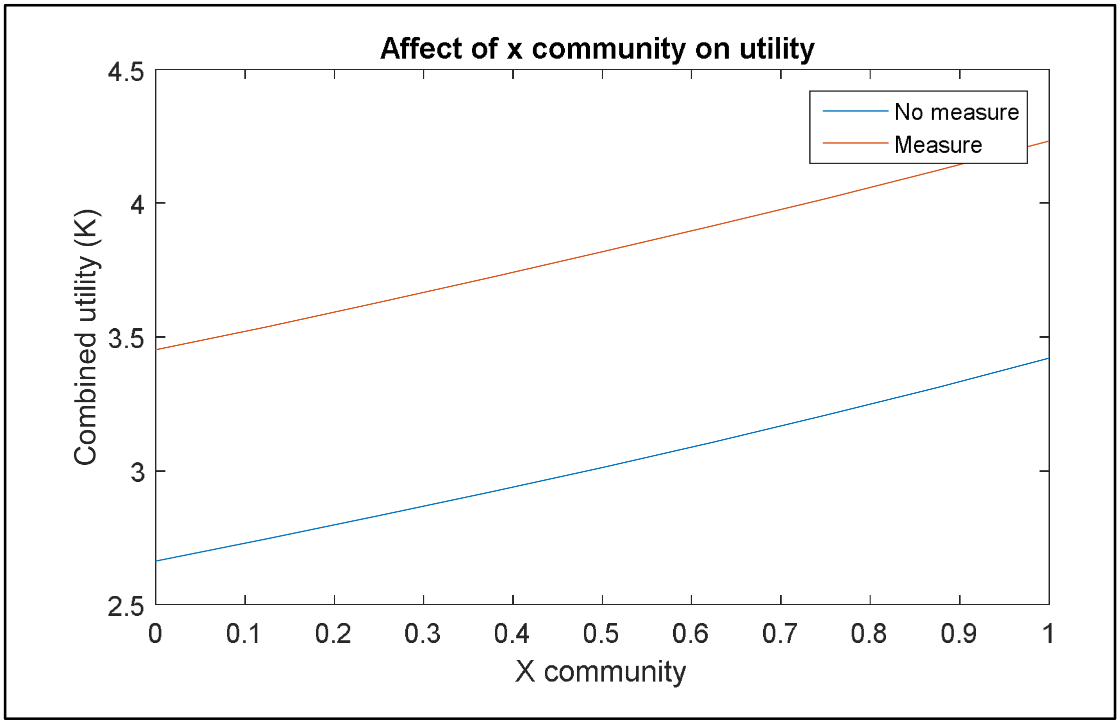

Fig. (6-21): Average community utilities before and after adding a measure (more effective).

6.8 Higher Cost of Repair

In this section, we have increased the cost of repair by 100% (twice as costly) compared to the baseline conditions. We are interested to see how a higher cost of repair affects the ABM results. Although it would first appear that the cost of repair may not affect homeowners much because it is assumed to be covered by the insurer, it affects the optimal value of the insurance premium rate which is part of the costs for homeowners. The summary of ABM outputs for this scenario is presented in Table (6-8).

Table (6-8): Summary of ABM output for higher cost of repair.

Description	**Values**
$ES_{\text{no upgrade}}$	\$415/year
ES_{upgrade}	\$71/year
$ER_{\text{no upgrade}}$	\$927/year
ER_{upgrade}	\$158/year
Rational discount rate	\$1200
Optimal annual insurance premium rate	\$873
Optimal annual discount	\$468
Homeowners' expected annual cost per house	\$2349
Proportion of homeowners who don't upgrade	83%

As expected, compared to the ABM outputs for the baseline conditions with a measure (Table 6-3), here we have much higher optimal insurance premium rates and also a higher optimal discount rate for the upgraded properties. When the repairs after flood damage are costly, it is reasonable for the insurer to increase the premiums and encourage more upgrades to prevent high flood damage in order to stay solvent. Higher insurance premiums lead to a higher average of total annual costs for homeowners compared to the baseline conditions. The number of upgraded properties is also higher in this community compared to the baseline conditions.

As shown in Figure (6-22), when the repairs are costly, protecting the community against flood damage by adding a flood control measure can greatly increase the utilities for the residents and the entire community. The large gap between the two curves in Figure (6-22) shows the important role of a measure in communities where repairs are costly.

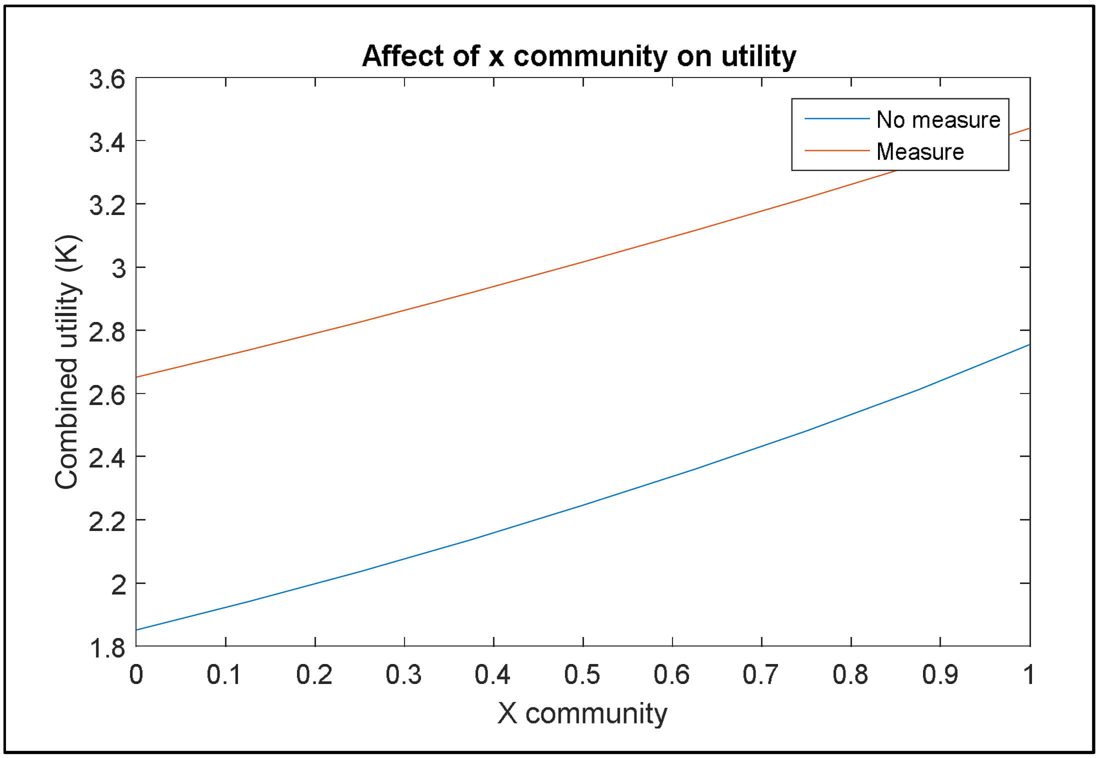

Fig. (6-22): Average community utilities before and after adding a measure (costly repairs).

6.9 Higher Cost of Suffering

In this section, we have increased the cost of suffering by 60% compared to the baseline conditions to study the effects of higher costs of suffering on the ABM results. The summary of ABM outputs for this scenario is presented in Table (6-9).

Table (6-9): Summary of ABM output for higher cost of suffering.

Description	**Values**
$ES_{no\ upgrade}$	\$664/year
$ES_{upgrade}$	\$113/year
$ER_{no\ upgrade}$	\$463/year
$ER_{upgrade}$	\$79/year
Rational discount rate	\$993
Optimal annual insurance premium rate	\$443
Optimal annual discount	\$89
Homeowners' expected annual cost per house	\$2180
Proportion of homeowners who don't upgrade	89%

In this scenario, the rational discount rate is lower than the ABM outputs for the baseline conditions (Table 6-3). Optimal insurance premiums and optimal discount rate are similar to the baseline as the cost of suffering is covered by the homeowners and does not directly affect the insurer. The average of total annual expected costs for the homeowners are higher which makes it more reasonable for the homeowners to upgrade and, therefore, the rate of upgrade is higher in this scenario.

As illustrated in Figure (6-23), adding a measure is quite beneficial to the residents and the community as there is a relatively large gap in between the two curves of total utilities after adding a measure (red curve) and with no measure intact (blue curve), with red being higher.

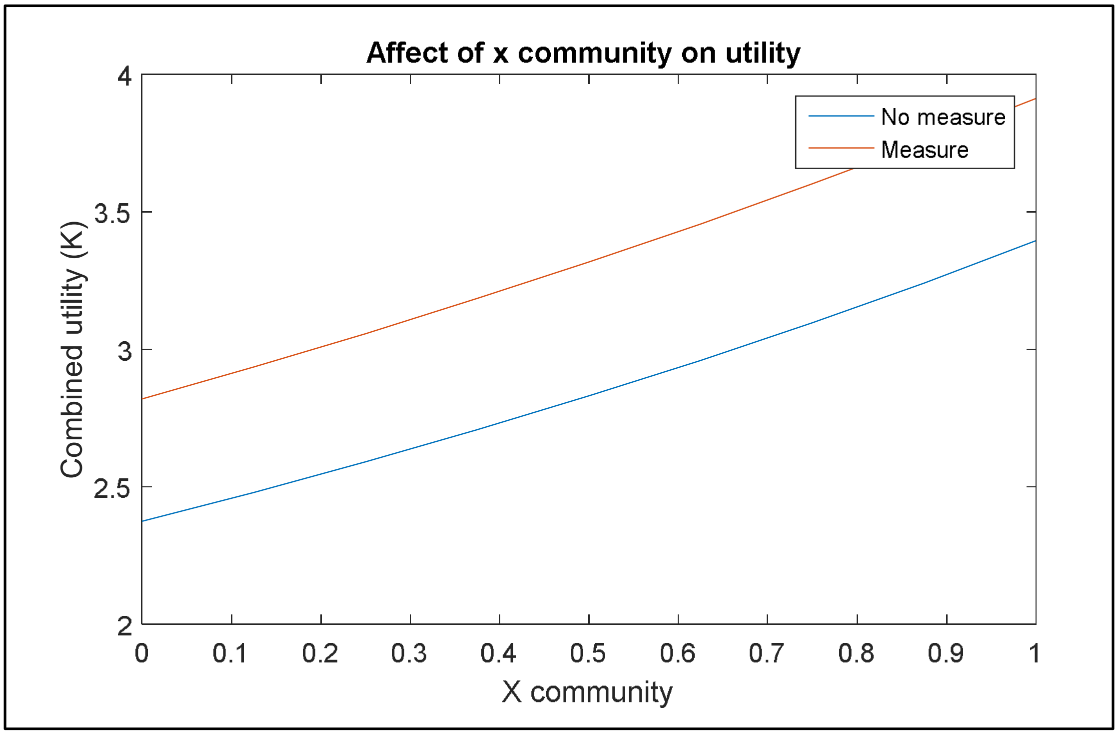

Fig. (6-23): Average community utilities before and after adding a measure (higher cost of suffering).

6.10 Conclusion

In this chapter, we demonstrated how the computational ABM can generate graphs of results that provide insights into the behaviors of the homeowners and insurer. It is shown how these behaviors are related to characteristics of the homeowners such as risk-aversion and affordability and the characteristics of the physical infrastructure, such as cost-effectiveness. We began with the ABM for baseline conditions as the model input parameters. Next, we compared the ABM results for the modeled scenarios to evaluate the effects of each parameter on the entire system. In each scenario, we compared the ABM results for the case of no measure and after the measure is intact. The average costs and utilities for different agents of the model were compared to understand how the addition of a measure affects each agent. This last relationship between a community measure and community collective resistance to storm events is useful in the development of a sociological perspective of resilience, which is presented in the next chapter.

Chapter 7

Integration of Linear Systems Concepts from Sociology

7.1 Introduction

In this chapter, we integrate quantitative methods from sociology to provide a theoretical basis for behaviors in community resilience that accounts for interactions at the individual and community levels. We draw upon the work by Coleman and Hao (1989), in which a mathematical framework is developed with micro-to-macro relations. Individual actors interact at the micro-level in a social exchange that is characterized by interest and control of resources. The resources are macro-level system components with systems-level properties such as values and constraints. The exchanges of and actor interests in resources are quantified using economic theory.

The intent of our work may have some differences from the original intent of Coleman and Hao's framework. For instance, we have interest in engineering aspects of community resilience as well as the behavioral aspects. We will need several layers of micro-to-macro relations with interactions between these layers, to reflect the fact that engineering resilience may affect behaviors that affect resilience and vice-versa. Furthermore, the computational ABM, which we will be integrating with linear systems theory, uses a combination of infrastructural and economic analysis with significant nonlinearities. Therefore, our work should not be judged by how closely it follows the original work by Coleman and Hao, but rather, the work by Coleman and Hao should be credited for the sociologically based systems-level qualitative thinking and quantitative relations that forms much of the theoretical background of our model for community resilience.

7.2 Application of Linear Systems Theory to Community Resilience

We begin with a figure that shows the relationship between individual action and system functioning, which is the same as Figure (1) of Coleman and Hao:

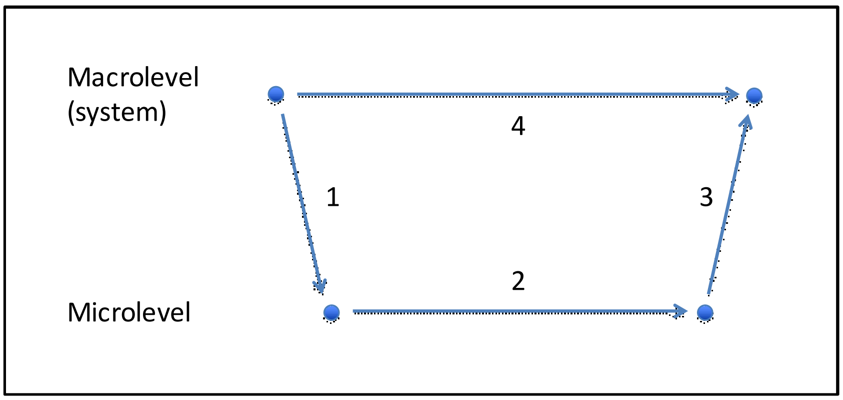

Fig. (7-1): Four basic relationships in describing macro- and micro-level system behavior.

To make this less abstract, we show how community resilience can be represented with this figure using three aspects of the system: engineering infrastructure, community economics, and social cohesion. We use the term layers, because we will need three of the above figure, one for each aspect, which can be visualized as being layered upon each other. In each layer, the macro-level is the community while the micro-level represents the set of homeowners residing in the community. It is noted while there is economics thinking that underlies the analysis of all three layers, the economics layer is focused on funding choices for the community measure and residential upgrades.

In Figure (7-2), the engineering infrastructure layer is shown. In the infrastructure disaster literature, disaster can be defined broadly [Quarantelli 1998]. For instance, measures of disaster can include sociological definitions of community dysfunction, quantified by community-wide descriptors of activity such as number of schools closed, number of hospital beds that must be abandoned, and number of power or water outages. An analysis of such types of disaster is beyond the scope of this thesis; nevertheless, we do indicate later in this chapter how the work herein can be developed further to incorporate such broader analyses.

Our definition of disaster is first defined at the individual (micro) level as damage of residences and the subsequent suffering of the homeowners. At the community (macro) level, we simply take the sum of the individual losses to represent community dysfunction. (In future work, a more sociological perspective can be included by modeling residents of the community who are diverted from their work duties to repair their homes and assist in recovery efforts.) The interactions between the individual and community levels occurs through the two types of flood hazard mitigators, residential upgrades and community protective measures, and through the price adjustments made by the non-profit insurer. These interactions can be complex, because the measures will affect the effectiveness of the upgrades, the insurers will need to increase fees for any measures and will offer discounts to induce upgrading, and the homeowners will react, in a rational economic manner to maximize their utilities. It is shown in the following how a three-layered analysis of the micro- and macro-level systems behaviors can be used to explore these interactions.

We begin the analysis of Figure (7-2) at the macro-level. Arrow 4 shows that community measures, such as levees, seawalls and storm surge barriers, will lead to a reduced risk of a disaster after a large storm. The community measure would also have significant impact at the micro-level, as indicated by arrow 1. In this case, the micro-level of the infrastructure is described in terms of the residential structures. The community measure would serve to reduce risk of flooding in the community, which would immediately translate to reduced risk of damage for every residential structure in the community that is in a flood risk zone. Next, we look at the impact of action at the micro-level on macro-level properties, shown as arrow 3. Here, upgrades of residential structures to better resist damage due to floods collectively leads to reduced risk of community dysfunction.

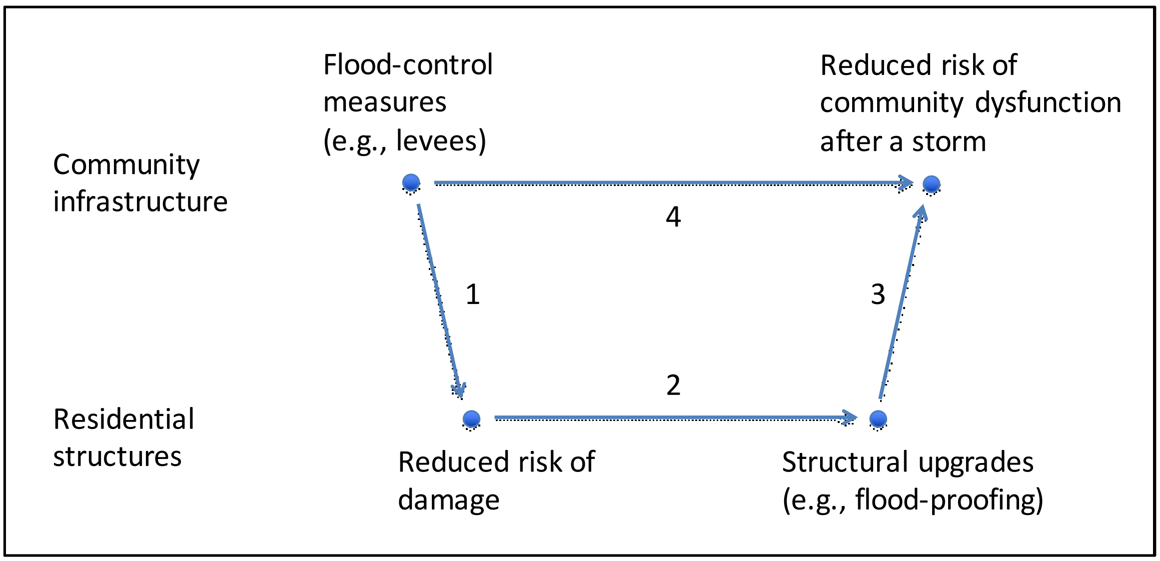

Fig. (7-2): Macro- and micro-level relationships for the engineering infrastructure layer.

The last relation, shown by arrow 2, is the most subtle from the system perspective. With the addition of flood-control measures at the community level, which leads to a reduced risk of damage at the individual residence level, there is less need for structural upgrade. Hence, the series of causal relations, 1, 2 and 3, will tend towards an increased risk of community dysfunction, which is the exact opposite of causal relation 4, which results in decreased risk. This diagram, by itself, is not sufficient to resolve the net effect of these contradicting effects. In a subsequent section, we will show how the computational ABM will provide the necessary quantitative relations.

Next, we examine the behavior aspects of community preparedness for disasters. Here, we note the fact that large community projects, such as the construction of measures to protect an entire community from storm damage, are driven by behaviors at the individual level. We use the term social cohesion to describe this layer of analysis, emphasizing the importance of individual cooperation for community preparedness. The need to separate and delineate community and homeowner behaviors will become even more apparent when looking at the economic aspects of resilience and preparedness.

Figure (7-3) shows the basic micro-to-macro relations for behaviors that are related to social cohesion. At the macro-level, arrow 4 indicates how a community that is unified and possesses a strong sense of identity will tend to promote actions, such as the construction of costly protective measures, to help ensure the function of the community after potentially damaging storms. While a community government would lead such efforts, the figure indicates that such an action would not be driven solely at this macro-level. Going backward from the top right node, we see in arrow 3 that community actions requires the support of the individuals that make up that community. In Figure (7-3), we indicate that such individual support is not an exogenous factor, but arises from the strength of community identity and cohesiveness that promotes homeowners' esprit de corps, shown in arrow 1, which then leads to individual support of community efforts, shown in arrow 2. It could be argued that arrow 1 should be bidirectional, since community cohesiveness is a characteristic of the aggregate behavior of individuals in the community. But we leave the arrow as leading from the macro-level to the micro-level at the start of model development. The arrow in the opposite direction is a characteristic of emergent behavior; this may be apparent towards the end of our systems analysis, when we include the results of the computational ABM.

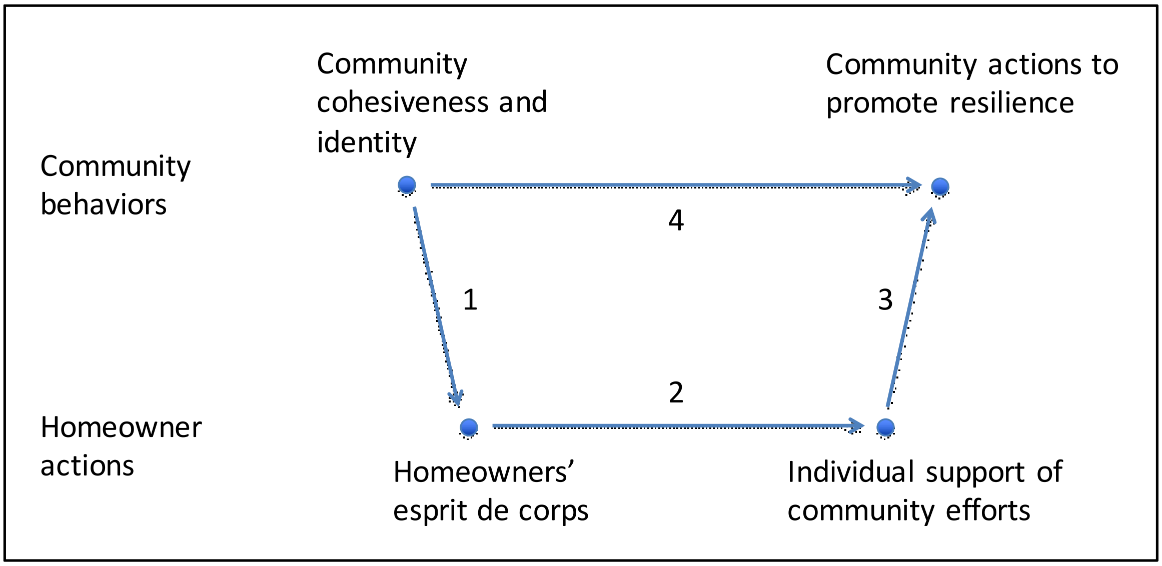

Fig. (7-3): Macro- and micro-level relationships for the social cohesion layer.

The behaviors of cohesiveness, esprit de corps, and the corresponding actions to support community resilience all have direct economic counterparts. In Figure (7-4), we show the economics layer in the context of funding for homeowner upgrades and community protective measures. We show this correspondence between behavioral and economic components of the system by comparing the corresponding nodes in Figures (7-3) and (7-4). Beginning with the top left node, we see that community cohesiveness and identity corresponds to the willingness and capacity for building community resilience. Proceeding to the right, we find that community actions correspond economically to funding these actions. The economic action implied by arrow 4, however, requires individual support because the funds ultimately come from the homeowners through taxation or other equivalent revenue collection methods. Continuing with identifying the correspondence between behavioral and economic aspects of building community resilience, we examine arrows 2 and 3. Here, homeowner's esprit de corps and subsequent support of community efforts correspond to homeowners emphasizing community economic needs, leading to a de-emphasis of upgrades of their own residences and funding of community measures.

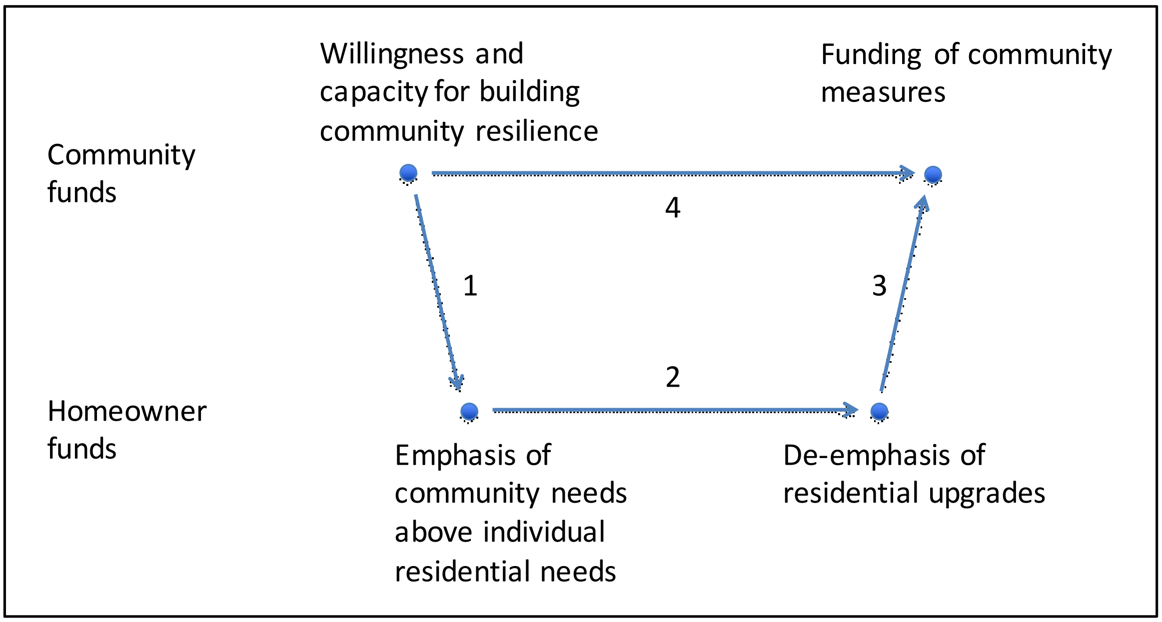

Fig. (7-4): Macro- and micro-level relationships for the economics layer.

It is noted that there is the negation of the characteristics at the micro-level. For instance, homeowners' lack of esprit de corps would be a focus on protecting their own residences, and the negation of support of community efforts would be support of their residential upgrades. There are other alternatives as well, such as the lack of sufficient support, whether at the community or individual residence levels. This situation would arise then the homeowners do not have enough additional resources to support these protective actions. In the figures we only illustrate the dominant behaviors; these other behaviors are included in the computational ABM.

The main motivation for introducing this three-layered systems analysis is to examine how rational decision-making of the residents in a community at the micro-level will not always behave in a manner that leads to the optimal economic outcome at the macro-level. For instance, it may be advantageous for the residents, regarded collectively, to pay for a community measure and to spend less on their own individual residential upgrades. But this does not necessarily mean that this advantageous pathway will be followed.

7.3 Resource Exchange Equations

In this section, we will use concepts of linear systems theory from Coleman and Hao (1989) to develop a set of conditions needed for the pathways described above to occur. The central notion in linear systems theory is resource exchange.

We use Figures (7-4) again, with highlights on the portions of these diagrams that we will model. We begin at the community level, as indicated in Figure (7-5).

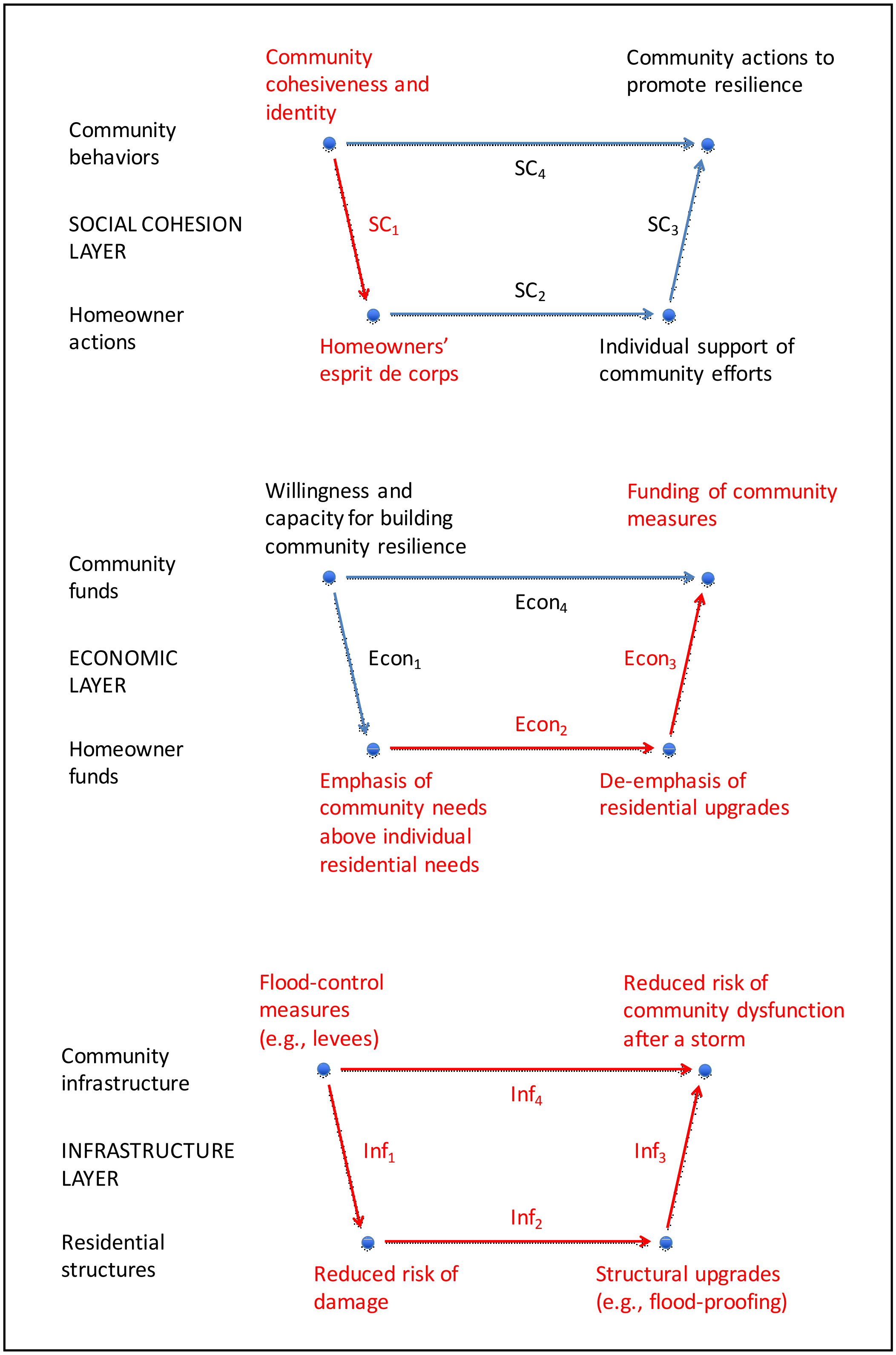

Fig. (7-5): Key relationships in the social cohesion, economic and infrastructure layers.

We begin at relation SC_1 shown in the left side of the social cohesion layer. We begin explaining the resource exchange starting with the community. The community offers to each resident i a resource $r_{\text{community},i}$ associated with community cohesiveness and identity:

$$r_{\text{community},i} = c_{\text{identity},i} v_{\text{identity}} \tag{7-1}$$

Here, v_{identity} quantifies the value of community identity that is not dependent on the homeowner, but is a constant parameter of the system. The coefficient $c_{\text{identity},i}$ represent the fraction of v_{identity} that is offered by the community to the resident. Since it is not necessary for all residents to be treated equally, $c_{\text{identity},i}$ would vary with resident i. As noted earlier, this resource is not financially based, but is an intangible asset that is offered by the community.

On the other side of the resource exchange is the contribution by each resident. A resident would need to consider two types of contributions to the community: as an individual homeowner and as an active member of the community:

$$r_{i,\text{community}} = c_{i,\text{homeowner}} v_{\text{homeowner}} + c_{i,\text{member}} v_{\text{member}} \tag{7-2}$$

The value $v_{\text{homeowner}}$ of an individual homeowner is not necessarily zero because there is collective value of residents who take care of their home. When residents of a community do not take care of their homes, the entire community suffers. The value of active membership to the community v_{member} can take several forms, and in the social cohesion layer this value is expressed in an abstract form. Here, we expect v_{member} to be significantly larger than $v_{\text{homeowner}}$. One of the fundamental relationships in linear systems theory is in the balanced exchange of resources:

$$r_{\text{community},i} = r_{i,\text{community}} + e_{\text{community},i} \tag{7-3}$$

in which $e_{\text{community},i}$ is a term that reflects the gap that may exist between the community and resident exchange of resources. In parameter estimation, these terms are typically minimized.

A community that seeks greater involvement of its residents would need to put resources into initiatives that would promote resident sense of membership. This may take many forms, ranging from supporting community activities to outreach efforts. The community would find ways to increase $c_{\text{community},i}$ for as many residents i as possible. If the community is successful, the homeowners would respond by increasing $c_{i,\text{member}}$. The difference between the community contribution $r_{\text{community},i}$ and the homeowner response $r_{i,\text{community}}$, as reflected by the gap-term $e_{\text{community},i}$, would be reduced if the community efforts are tailored towards the residents preferences.

Next, we explore alternate expressions of value of homeowners and community members in the economics and infrastructure layers. In the infrastructure level, we examine the exchange of resources between the insurer and the homeowners for individual (micro-level) upgrades and community (macro-level) protective measures. We compare the cost of residential upgrades and community measures with the expected cost of damage from a natural hazard. We use the computational ABM to determine most of the key quantities, including the expected costs of repair and suffering and the optimal insurer fees and discounts.

For the upgrades, we begin by examining the difference in the expected cost of repair when there is no measure. This is the monetary value of the upgrade in terms of structural protection:

$$v_{\text{upgrade}} = \text{ER}_{\text{no upgrade}} - \text{ER}_{\text{upgrade}} \tag{7-4}$$

Next, we assess the value of a measure by determining the reduction in the expected cost of repair due to the protective abilities of the measure. This value is dependent upon whether the residence was upgraded or not:

$$v_{\text{measure (upgrade)}} = \Delta\text{ER}_{\text{upgrade}} \tag{7-5}$$

$$v_{\text{measure (no upgrade)}} = \Delta\text{ER}_{\text{no upgrade}}$$

and is computed in a straightforward manner:

$$\Delta\text{ER}_{\text{upgrade}} = \sum_{j=1}^{N} \sum_{k=1}^{M} \text{P}\,[\text{storm}_j] * \Delta\text{P}\,[\text{damage}_k \,|\, \text{storm}_j, \text{upgrade}] * \text{C}_{\text{repair,k}}$$

$$\Delta\text{ER}_{\text{no upgrade}} = \sum_{j=1}^{N} \sum_{k=1}^{M} \text{P}\,[\text{storm}_j] * \Delta\text{P}\,[\text{damage}_k \,|\, \text{storm}_j, \text{no upgrade}] * \text{C}_{\text{repair,k}} \tag{7-6}$$

in which $\Delta\text{P}\,[\text{damage}_k \,|\, \text{storm}_j, \text{upgrade}]$ and $\Delta\text{P}\,[\text{damage}_k \,|\, \text{storm}_j, \text{no upgrade}]$ are the reductions in probability of damage due to the protective ability of the measure.

The insurer provides a discount for an upgrade, and this can be considered as the value that takes into account the homeowners' risk, affordability, suffering (which govern purchasing behavior) as well as the cost of repair (which is entirely borne by the insurer).

In this case the resource exchange is as follows:

$$r_{\text{insurer}} = \text{Insurance discount}_{\text{opt}} \tag{7-7}$$

$$= C_{\text{upgrade}} - (ES_{\text{no upgrade}} - ES_{\text{upgrade}}) - C_{\text{risk,opt}}$$

$$= \text{Rational discount rate} - C_{\text{risk,opt}}$$

$$r_{i,\text{upgrade}} = \text{Rational discount rate} - C_{\text{risk},i}$$

The insurer provides the insurance discount optimized with respect to all homeowners as explained in Chapter 5. This would correspond to a specific value of the cost of risk, which is denoted as $C_{\text{risk,opt}}$. Homeowner *i*, on the other hand, would have a their own value for the cost of risk, $C_{\text{risk},i}$, which, in general, would be different from the optimal value. This would lead to the following resource exchange relation with an error given by the difference between the optimal cost of risk and homeowner's cost of risk:

$$r_{\text{insurer}} = r_{i,\text{upgrade}} + e_{i,\text{upgrade}} \tag{7-8}$$

$$e_{i,\text{upgrade}} = C_{\text{risk,opt}} - C_{\text{risk},i}$$

It is noted that the error is always non-negative. If it is negative, so that the homeowner's cost of risk is greater than the optimal value, then the homeowner will upgrade their residence. When the error is positive, then it is not worthwhile for the homeowner to upgrade, and the resource exchange becomes:

$$r_{\text{insurer}} = e_{i,\text{no upgrade}} \tag{7-9}$$

in which the homeowner has zero contribution (no upgrade) and the error is simply given by the insurer's discount. The preceding relation would also hold if the homeowner cannot afford the upgrade.

The above describe all of the resource exchanges that underlie the relationships, Inf_1 – Inf_4, in Figure (7-5); these exchanges are evaluated through the nonlinear computational ABM.

In the economics layer, we examine the two relations, $Econ_2$ and $Econ_3$, which begin at the individual and ends at the community. Here, we consider the cost of risk and cost of suffering in addition to the costs of any upgrades and community protective measure. The decision here is not between an upgrade versus a community measure: these are not mutually exclusive choices. The complex, economic-based decision making that involves upgrades, measure and insurer fees has already been analyzed by the computational ABM. Instead, the decision is between individual homeowners assessing their own economic situation versus the collective economic status of their community.

The homeowner assessment is at the micro-level while the collective status is at the macro-level. Coleman and Hao use utility theory in the analysis of micro- and macro-level decisions, and we follow this approach here. There are some departures from their original mathematical formulation, primarily because we use our computational ABM results to help us compute some of the terms in the utility function, but we believe we retain their essential ideas.

We have already introduced the notion of homeowner utility, U_i, in equation (5-16) and repeated below, in terms of the utility of a homeowner as an individual, $U_{i,\text{individual}}$, and the utility of a homeowner as a member of the community, $U_{\text{community}}$. These two utilities correspond to the micro- and macro-levels, respectively.

$$U_i = U_{i,\text{individual}}^{1-x_i} U_{\text{community}}^{x_i} \tag{5-16}$$

As noted in section 5.9, the exponent x_i is related to the degree to which the homeowner acts in the interest of the community. Hence, it is natural to expect a relationship between this exponent and the fraction $c_{i,\text{member}}$ of membership value v_{member} that homeowner i contributes to the community. We express this in the following general form:

$$x_i = f\left(c_{i,\text{member}}\right) + e_{i,\text{member}} \tag{7-10}$$

In this manner, the community and economics layers are linked. The residual term $e_{\text{member},i}$ indicates that community membership does not always translate directly to support of community activities, which in the present case is the financing of a protective storm measure. The infrastructure layer is also linked to the economics layer through the computational analysis of the utilities $U_{i,\text{individual}}$ and $U_{\text{community}}$.

7.4 Deciding on the Community Measure

We are now ready for the final, and in many ways, most important decision in the model, which is to build or not build a community measure. This is a binary decision which proceed with the following steps:

1. Building community support for the measure.
2. Voting or other community process on deciding to build the measure.
3. Taxation to fund the measure.
4. Design and construction.
5. Impact on community resilience to future storms.

The computational ABM already incorporates taxation (step 3) through an increase in insurer fees, as well as the design, construction and subsequent future impact on resilience (steps 4 and 5) through decreases in probabilities of damage and expected costs of repairs.

With the sociology-based linear systems theory, we have shown, through the links between the social cohesion layer and economics layer, how it is possible to build support for the measure (step 1). We also have explained how the computational ABM and linear systems theory can be combined to determine the following utility functions:

$$U_i = U_{i,\text{individual}}^{1-x_i} U_{\text{community}}^{x_i} = \text{utility for homeowner } i \text{ (no measure)} \quad (7\text{-}11)$$

$$U'_i = U'^{1-x_i}_{i,\text{individual}} U'^{x_i}_{\text{community}} = \text{utility for homeowner } i \text{ (with measure)}$$

If the community process for decision-making (step 2) was through voting, then we can determine the outcome of the vote by a simple count:

$$\text{Proportion favoring a measure} = \frac{\text{number of homeowner } i \text{ with } U'_i > U_i}{\text{total number of homeowners}} \qquad (7\text{-}12)$$

While this is straightforward to determine using the computational ABM, and we can gain further insights by examining a few of the plots shown in Chapter 6. We will be able to identify resource exchange at various levels and the error terms in these exchange relationships.

We begin with Figure (7-6), which shows the scattergram of utilities, in which, as described earlier, the horizontal direction is for the utility without a community measure, the vertical direction is for the utility with the measure, and each point represents an individual homeowner. The 45-degree line represents the special case when the utilities with and without the measure are identical; we label this as the indifference line because homeowners that lie on this line would be not be affected by the measure and would be indifferent to the vote outcome. The points (with jitter to aid in visualizing the density of points) are nearly all for the case where the exponent $x = 0$, in which the homeowners assess utilities according to their own self-interest. There is one point, indicated in the figure, which corresponds to the case were the exponent $x = 1$, in which the homeowners all assess utilities according to the average utilities of every member of the community. For other values of the exponent x, the points would lie between these two extreme cases; this was explored in depth in the previous chapter. Equation (7-12) corresponds to the proportion of points above the indifference line. For the particular example shown here, it is clear that the measure will pass a majority vote regardless of the value for x.

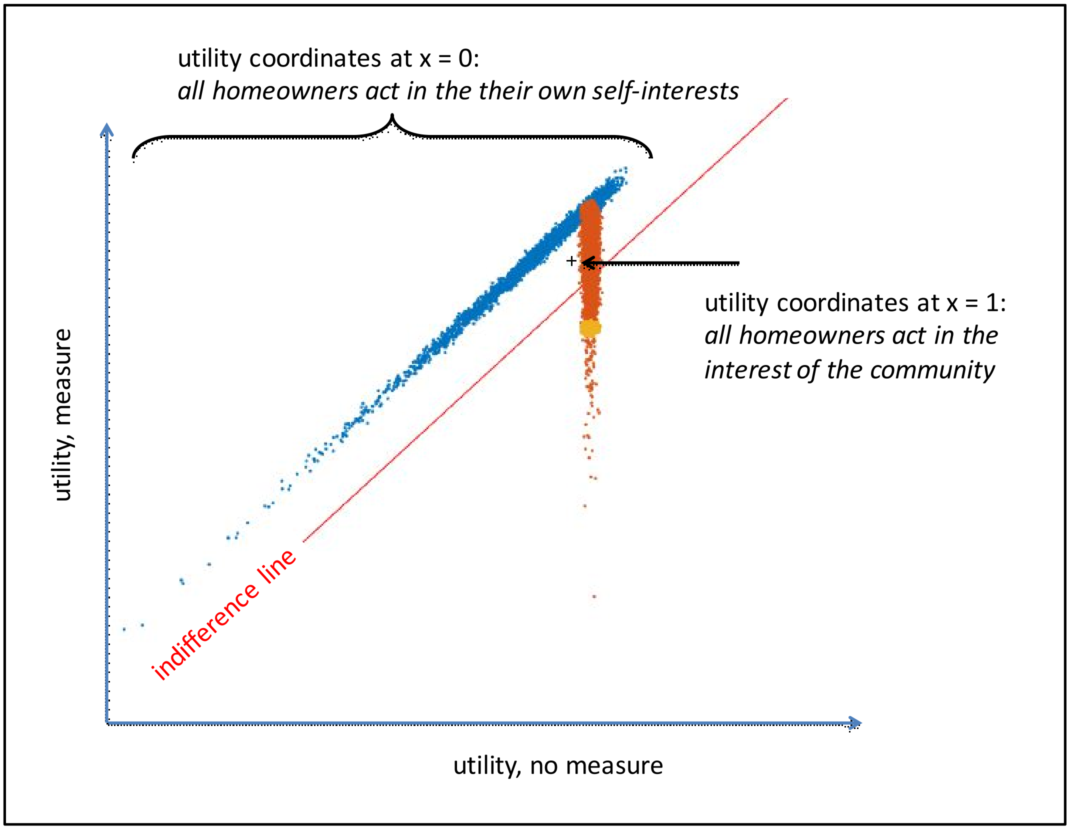

Fig. (7-6): Scattergram of household utilities with and without a community measure.

This view of voting, however, is too simplistic, given the influences that a subset of voters can use to alter the process. These influences include advertising, political pressures, and many other activities. While it is beyond the scope of this thesis to explore these influences, we can still model a slightly different version of the voting process by using a weighted sum instead of a simple sum in equation (7-12). It is useful to define a binary indicator variable

$$I_i = \begin{cases} 1, & \text{if } U'_i > U_i \\ 0, & \text{otherwise} \end{cases} \tag{7-13}$$

Referring to Figure (7-6), $I_i = 1$ for all of the points above the 45-degree line and $I_i = 0$ for all of the points below the line. We also need to define an index set of influential homeowners

$$J = \{j\text{: homeowner } j \text{ has extraordinary influence on the voting process}\}$$

Then the weighted proportion is defined as follows:

$$\text{Weighted proportion favoring a measure} = \frac{\sum_{j\in J} w_j I_j + \sum_{i\notin J} I_i}{\sum_{j\in J} w_j + \sum_{i\notin J} 1} \tag{7-14}$$

Where w_j is the degree of influence of homeowner $j \in J$, scaled so that $w_i = 1$ would correspond to the weight of a non-influential homeowner $i \notin J$. If the influential homeowners were randomly scattered throughout the homeowners shown in Figure (7-6), then the weighted proportion would be approximately equal to the original unweighted proportion in equation (7-12). If, however, the influential homeowners were predominantly below the indifference line, then, with sufficiently high influence, as quantified by the weights w_j, the proportion can change to above 50% to below 50%, resulting in a reversal of the vote outcome.

It is worthwhile to explore the points in Figure (7-6) in more detail to determine the homeowner characteristics associated with location of the points with respect to the indifference line. We find that there are 5 groups of households, which are labeled in Figure (7-7). To interpret the characteristics of these groups, we use the scattergrams in Figure (7-8) where were also shown in the preceding chapter. We recall that the points in these scattergrams show the affordability of each household in the horizontal direction and the total expected cost, including the insurance fee along with the costs associated with risk and suffering, in the vertical direction. The points are shifted downward when there is a measure because of the reduced probability of damage, which lowers the expected cost of suffering.

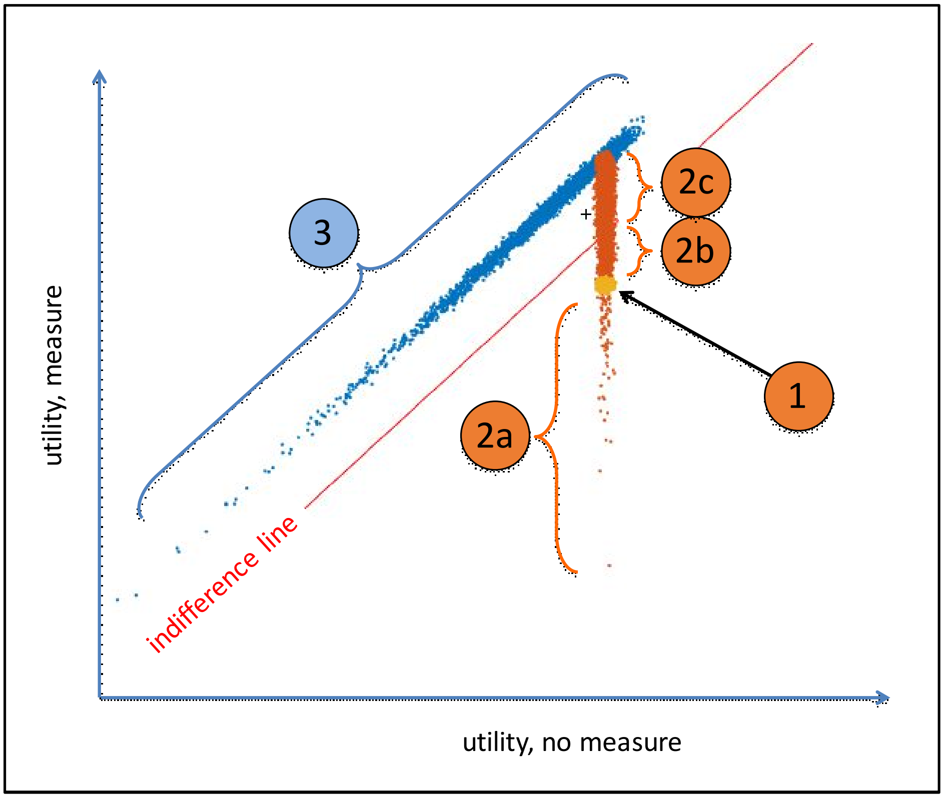

Fig. (7-7): Groups of households in the utility scattergram.

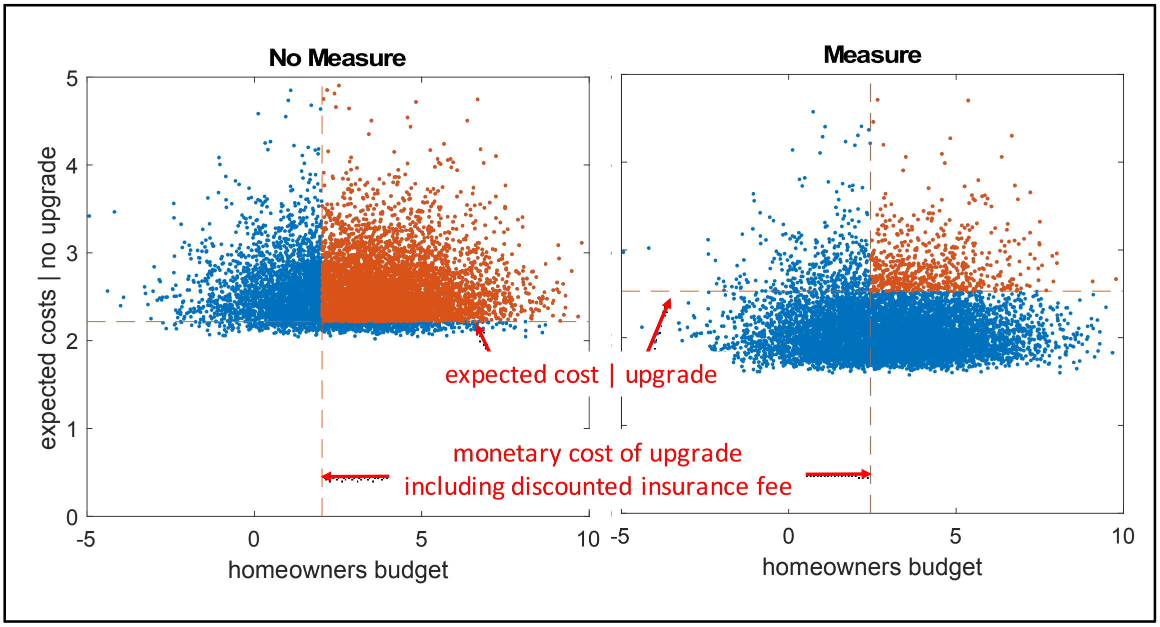

Fig. (7-8): Scattergrams of household budgets and expected costs with respect to upgrades and measure.

The horizontal dashed lines are the expected costs when there is an upgrade. This line may be higher for the community with a measure because any reduction in the expected cost of suffering may be offset by reductions in the insurer discount. The vertical dashed lines are the monetary cost of upgrade that includes the insurance fee and discount. This line is shifted to the right when the discount is reduced.

We are now ready to show the relationship between the points in Figures (7-7) and (7-8). This relationship requires a detailed examination of the points in Figure (7-8) and their positions with respect to both pairs of dashed lines. To make this clear, we examine only one representative point for each of the 5 groups in Figure (7-7). We need to show each of these points twice: once without the community measure and again with the measure. These 5 pairs of points are shown schematically in Figure (7-9) along with the two pairs of dashed lines that were defined in Figure (7-8).

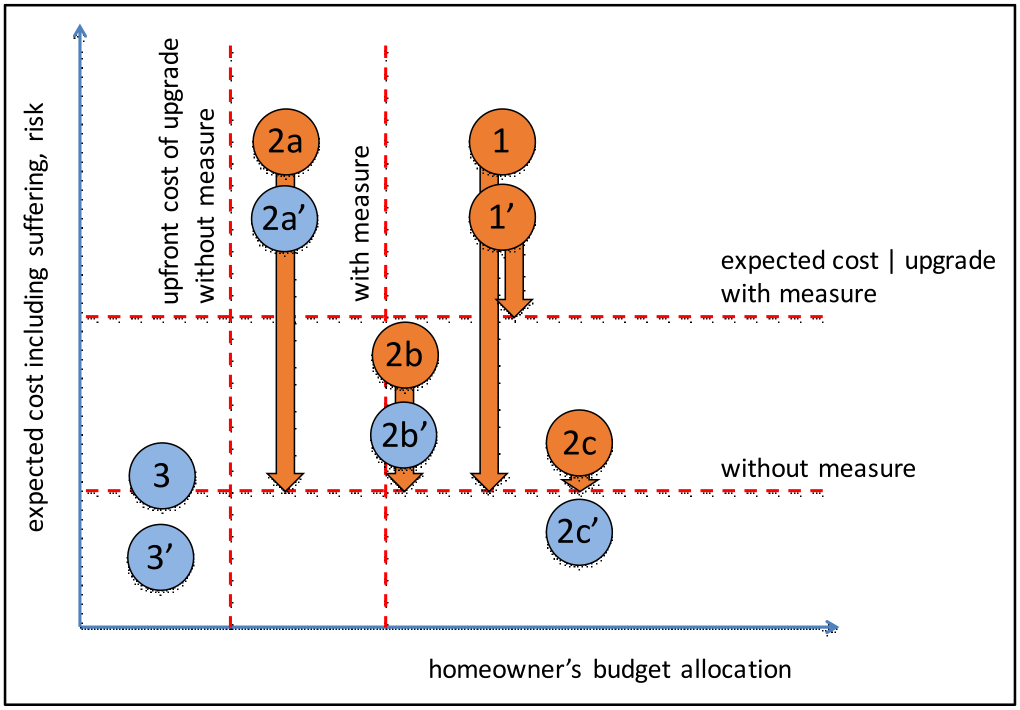

Fig. (7-9): Schematic diagram showing a representative household for each of the 5 groups indicated in Figure (7-7) plotted with respect to the horizontal dashed lines from Figure (7-8).

We explain these pairs of points in sequence. It is noted that the diagram contains all of the information needed to explain the differences between each group of households, and the text below only provides some supplementary text to clarify these difference.

1. <u>Upgrade with and without the measure</u>. These households are indicated as red points in both of the plots of Figure (7-8). These household can afford the cost of the upgrade, and will have lower expected cost if they choose the upgrade option, regardless of whether the community measure is built or not. Hence, the expected cost and utilities for this group of household are the same. Since the expected cost with the measure is higher than that without the measure, the point associated with this group of households will be below the indifference line, as shown in Figure (7-7). In Figure

(7-9), we show a representative point for this group of households as point 1 without the measure and point 1’ with the measure. As explained earlier, the point with the measure is below and to the right of the corresponding point without the measure. The red arrows to the dashed lines indicate that this household will choose to upgrade regardless of the status of the measure. Points 1 and 1’ are also shown in the left plot of Figure (7-10), where the total expected cost of this group is compared for the cases where there is no community measure (point 1) and when there is a measure (point 1’).

2. Upgrade without the measure, no upgrade with the measure. These households are indicated as red points in the left plot of Figure (7-8) and change to blue in the right plot. There are three subgroups to consider:
    a. Measure makes the upgrade unaffordable. The difference between this group and group 1 is that the expected cost with the measure is associated with no upgrade, which will be higher than that associated with upgrade. Hence the utility with the measure is lower than that for group 1. This is indicated in Figure (7-7), where the points associated with group 2a lie below those associated with group 1.
    b. No measure and upgrade is preferred to measure with no upgrade. In this case, the expected cost for the upgrade is higher than that without the upgrade, so the homeowner will opt not to upgrade. The

utility with the measure will be higher than that for group 1 but still below the indifference line.

c. Measure and no upgrade is preferred to no measure with or without upgrade. Here, the measure increases the utility of no upgrade sufficiently high so that it is above the utilities associated with all other cases - upgrade with measure and upgrade or no upgrade without the measure. Hence, the utility with the measure is above the indifference line.

3. No upgrade. This includes all cases where the homeowner does not upgrade, including unaffordability and higher expected costs associated with an upgrade. These households are indicated as blue points in both of the plots of Figure (7-8), Figure (7-7) and the right side of Figure (7-10).

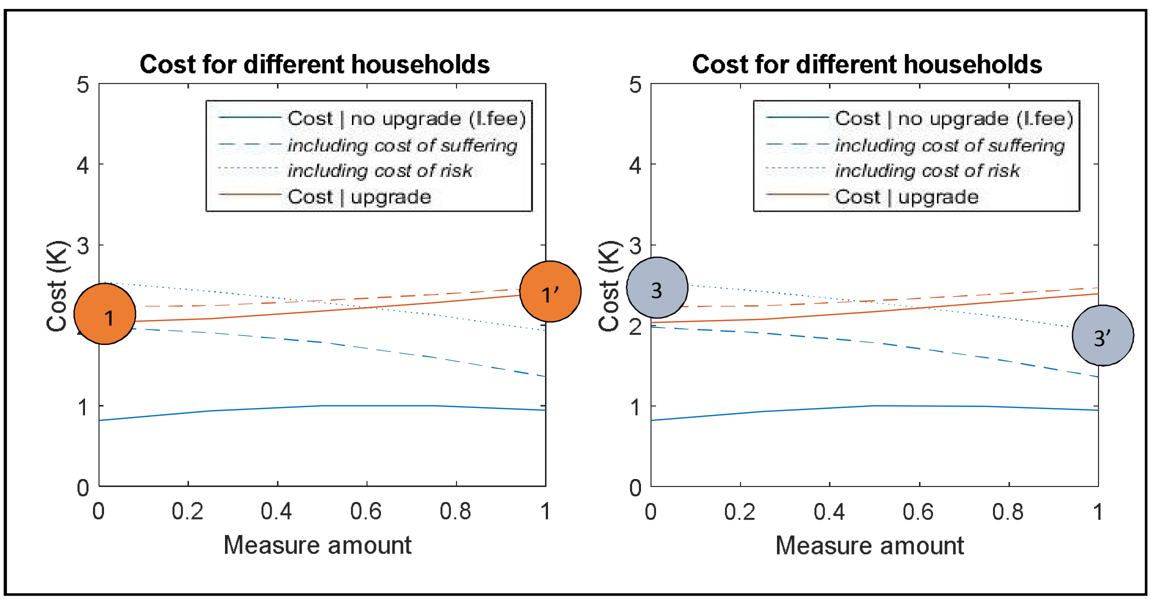

Fig. (7-10): Total expected cost given upgrade or no upgrade, plotted with respect to the measure, with household groups indicated in circles.

We also show representative points in the original scattergrams in Figure (7-11).

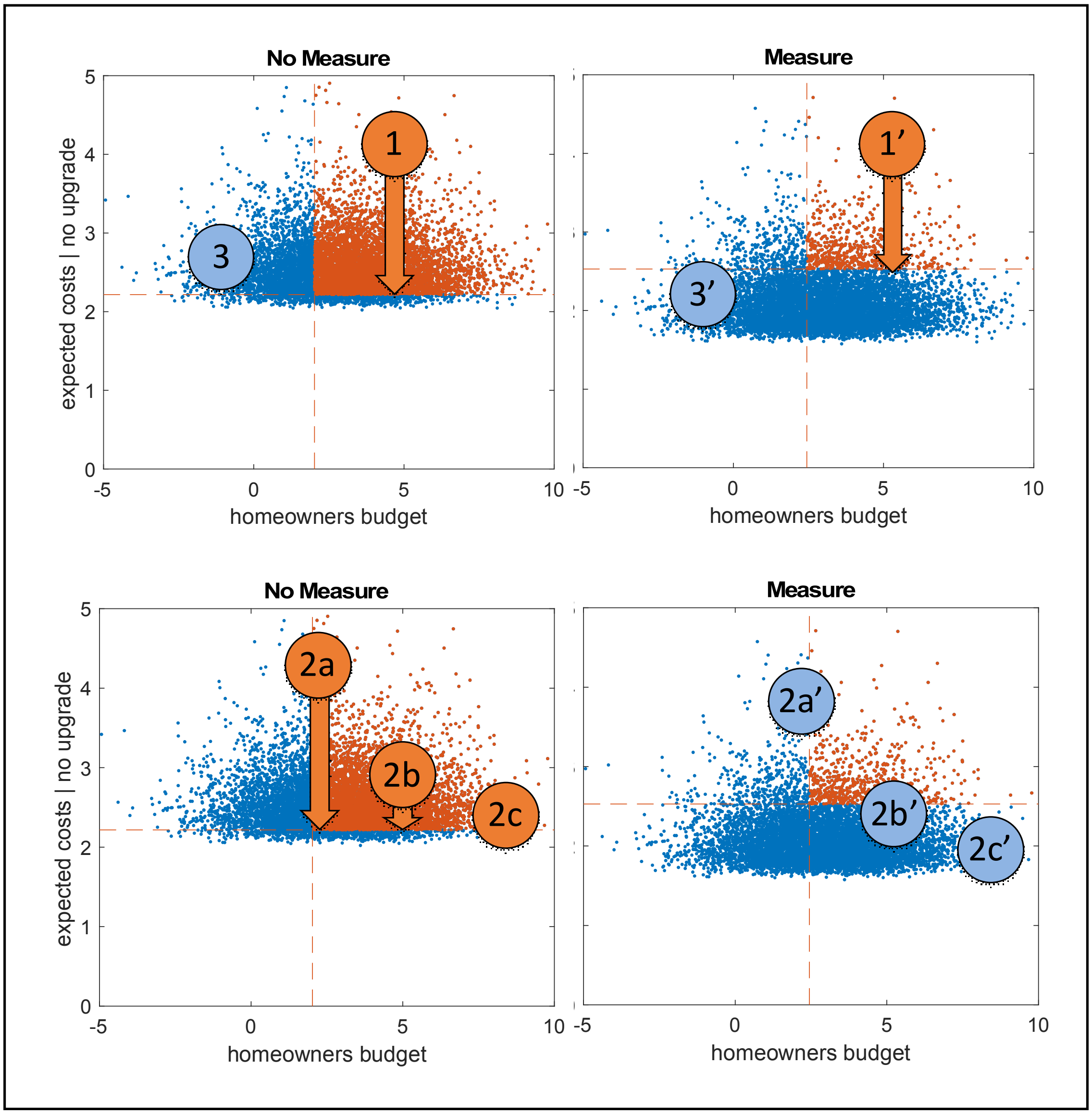

Fig. (7-11): Representative points for each of the 5 groups of households.

Returning to the weighted voting problem, it can be seen that the groups that prefer not to have the measure are groups 1, 2a and 2b. These groups tend to be wealthier because they all must be able to afford the cost of the upgrade. Furthermore, they tend to be towards the upper portion of the scatterplots in Figure (7-11), which are the ones with the highest costs of risk. These homeowners are most likely to upgrade their residences regardless of the status of the measure.

There are two ways to reduce the sizes of these groups:

1. Infrastructure level
    a. Increase the effectiveness of the measure.
    b. Reduce the cost of the measure.
2. Social cohesion level:
3. Increase the fraction $c_{i,\mathrm{member}}$ of membership value v_{member} that homeowner *i* contributes to the community, which would lead to an increase in the exponent *x* in the utility function.

7.5 Incorporating System Dynamics Concepts into the Linear Systems Framework

We conclude our analysis of the linear systems framework by presenting an alternate view of the three-level processes of community infrastructure building. We use concepts from system dynamics, which is a branch of systems science that has found applications in many areas of social science [Meadows, 1999; Sterman, 2000; Forrester, 2009] and public health [Hirsch, et al. 2007; Mabry, et al. 2008]. It has been argued that methods, such as system dynamics, that can show the complex feedback mechanisms in societal processes are vital for policy formulation [Warren, 2004] and for addressing implementation and sustainability issues [Stirman, et al., 2012]. Furthermore, these methods can be effective as communication tools that can engage stakeholders such as community groups and policy makers in systems thinking [Hovmand, 2013].

System dynamics is a subfield of systems science that encompasses a wide range of methods that are related primarily in the use of causal relationships that involve feedback loops. The most basic system dynamic method is the development of causal loop diagrams; here, the process of developing the diagram is as important or can even be more important than the diagram itself [Hovmand, 2013]. The most computational system dynamics method involves so-called stock-and-flow models [Forrester, 2009]. There are three types of variables in stock-and-flow models: *stocks*, which represent quantities that are accumulated or depleted over time; *flows* that increase or decrease the levels of the stocks; and *auxiliary variables*, which are constants that parameterize the model. These constructs are often related to exogenous influences, and can affect both the stocks and flows. The relationships between the stocks and flows can be formalized using differential equations and other mathematical operations; however, as shown herein, diagrams of stocks and flows are informative even without the mathematical representation. We do not develop a computational stock-and-flow model because the ABM presented in Chapter 5 is far better suited to account for the multiple levels of interactions between the individual homeowners and the insurer. A series of conceptual stock-and-flow models are used as a visualization tool that can be helpful in communicating the complex processes in community resiliency towards storm surges.

We begin with Figure (7-12), which shows the stocks and flows associated with the infrastructure layer. Here, damage is a stock that used as a measure of the expected amount of damage due to a storm surge. The other two stocks are upgrade decision and no upgrade decision, which are used as measures of the proportion of homeowner who are deciding to upgrade or not upgrade. It is noted that the stocks refer to expected events of the future: there is at present, no damage, and no finalized decision regarding upgrading. For instance, if the cost of upgrade is raised, then there would be a migration of homeowners from the upgrade decision stock to the no upgrade decision stock. This migration would not be possible if the upgrades were already built.

The flows in this diagram are to or from these stocks. For instance, the migration that was just mentioned would be a flow through the double arrow at the bottom of the figure. The double triangle represents a value that regulates this flow. Continuing with the migration example, a rise in the cost of upgrade will cause the valve, supporting no upgrade decision, to open, resulting in a flow from the upgrade decision stock to the no upgrade decision stock. There are three other flows in the diagram. In the middle, there is a flow from the no upgrade decision stock to the upgrade decision stock, which is in the exact opposite direction of the flow just described. An arrow is shown from the damage stock to the supporting upgrade decision valve. This implies that an increase in the damage stock would lead to an opening of this valve. This is expected because an increased expectation of future damage would cause an increase in the proportion of homeowners who will decide to upgrade. The damage stock has flows associated with increased and reduced risk of damage. The arrow from the upgrade decision stock to the reduced risk of damage valve indicates that when a larger proportion of homeowners choose to upgrade the extent of expected damage will reduce.

A minus sign with a counter-clockwise arrow is also shown in the stock-and-flow diagram. This indicates the presence of a so-called balancing loop (Meadows, 1999). This balancing loop is represented by the series of connected arrows that begins at damage, proceeds to upgrade decision, and returns back to damage. It can be seen that increases in the damage stock will cause an increase in the upgrade stock, which then causes a decrease in the damage stock. It is a checks-and-balance loop in which an increase in the initial stock, which is damage in this case, causes the system to respond by decreasing this same stock. This counteracting influence typically results in a stable equilibrium state.

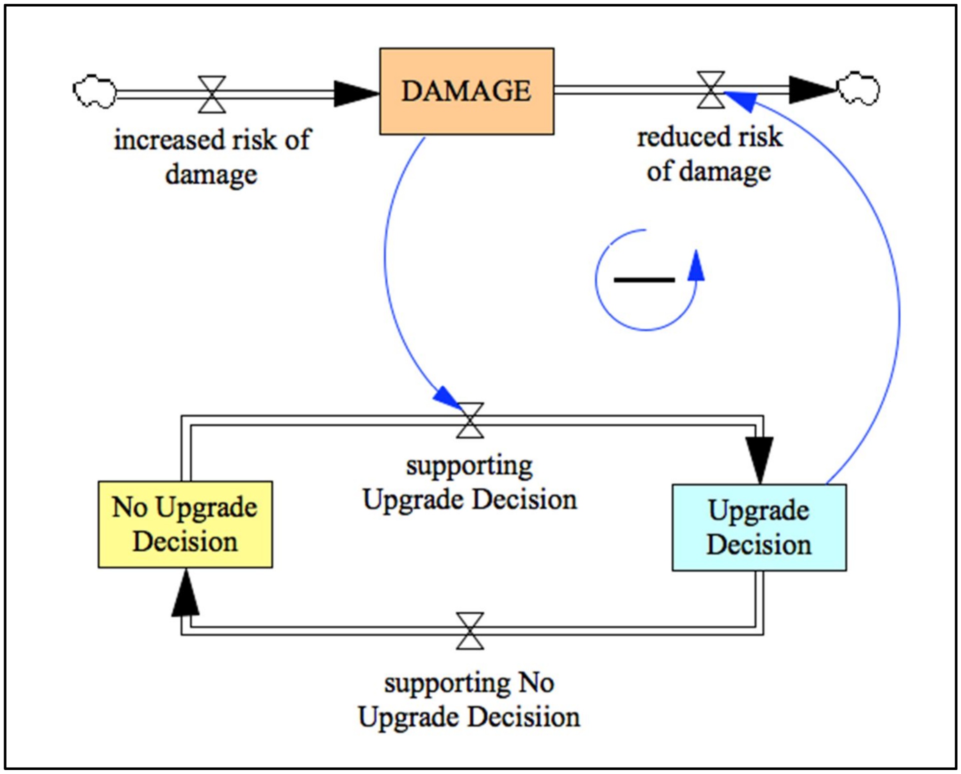

Fig. (7-12): Stock-and-flow diagram of the infrastructure layer.

Next, we provide a simplified representation of the economics layer by adding one more stock in the preceding diagram, as shown in Figure (7-13). This is the <u>fees</u> stock, which represents the total amount of insurer fees paid by the homeowners. There are two additional flows, which are simply associated with increases and decreases in the fees. The plus sign with the counter-clockwise arrow indicates the presence of a so-called reinforcing loop (Meadows, 1999). This reinforcing loop is easiest to understand if we begin with the flow associated with an increase in fees. This increase will cause some homeowners who had been considering the upgrade option to switch to the no upgrade option because of affordability constraints, as indicated by the arrow from the fees stock to the supporting no upgrade decision valve. With more homeowners in the no upgrade decision stock, the community as a whole will suffer with an increased risk of damage, as indicated by the arrow to the valve with that same name. The insurer will need to pay for these damages, and since the insurer is not-for-profit, all costs must be passed on back to the homeowners, which is indicated by the arrow back to the increase in fees valve. All of these arrows are associated with positive causality, starting from increasing fees, which force more homeowners to opt for no upgrades, leading to greater expected damage, and resulting in an even further increase in fees. This is a spiraling effect that typically leads to exponential increases. It is noted that the exact opposite can also occur, with all influences reversing sign: A decrease in the fees can lead to fewer homeowners opting for no upgrades, which leads to reduced expected damage, resulting in an even further decrease in fees. This is also a spiraling effect that typically leads to an exponential decay towards zero.

It is noted, however, that these spiraling effects, leading to exponential increases or decays, represent only one pair of tendencies of the system. The other balancing loop, shown in Figure (7-12), is also in effect and will serve to counteract the spiraling effects of the reinforcing loop of Figure (7-13). In Figure (7-14), we show the stock-and-flow diagram with both sets of loops. Figure (7-15) shows an additional reinforcing loop of the stock-and-flow diagram, which was not shown in Figure (7-14) to avoid overlapping of the loops. At this point, some of the limitations of the stock-and-flow diagram are noted. It is a simplification of the system, which can be useful in visualizing the co-existence of multiple processes, but does not account for other factors such as the cost of risk, the differences between cost of repair and cost of suffering, and the affordability constraint. Furthermore, the diagram can only represent behaviors at the aggregate level. It has been shown that there are many individual-level interactions that influence pricing and decision-making at the household and community levels. Hence, it is not worthwhile to use the diagram to develop a computational stock-and-flow model; it serves best as a visualization tool. Instead, the ABM is used for all of the computations in this part of the model, as explained later in this chapter. The flows, such as that of the households who switch from the “No Upgrade Decision” to “Upgrade Decision” stocks or of the funds that fill the “Fees” stock, would be computed by the ABM when a parameter, such as the cost of the upgrade, changes. System dynamics equations would not be used because the multiple interactions and resulting flows determined from the ABM cannot be easily expressed in terms of ordinary differential equations.

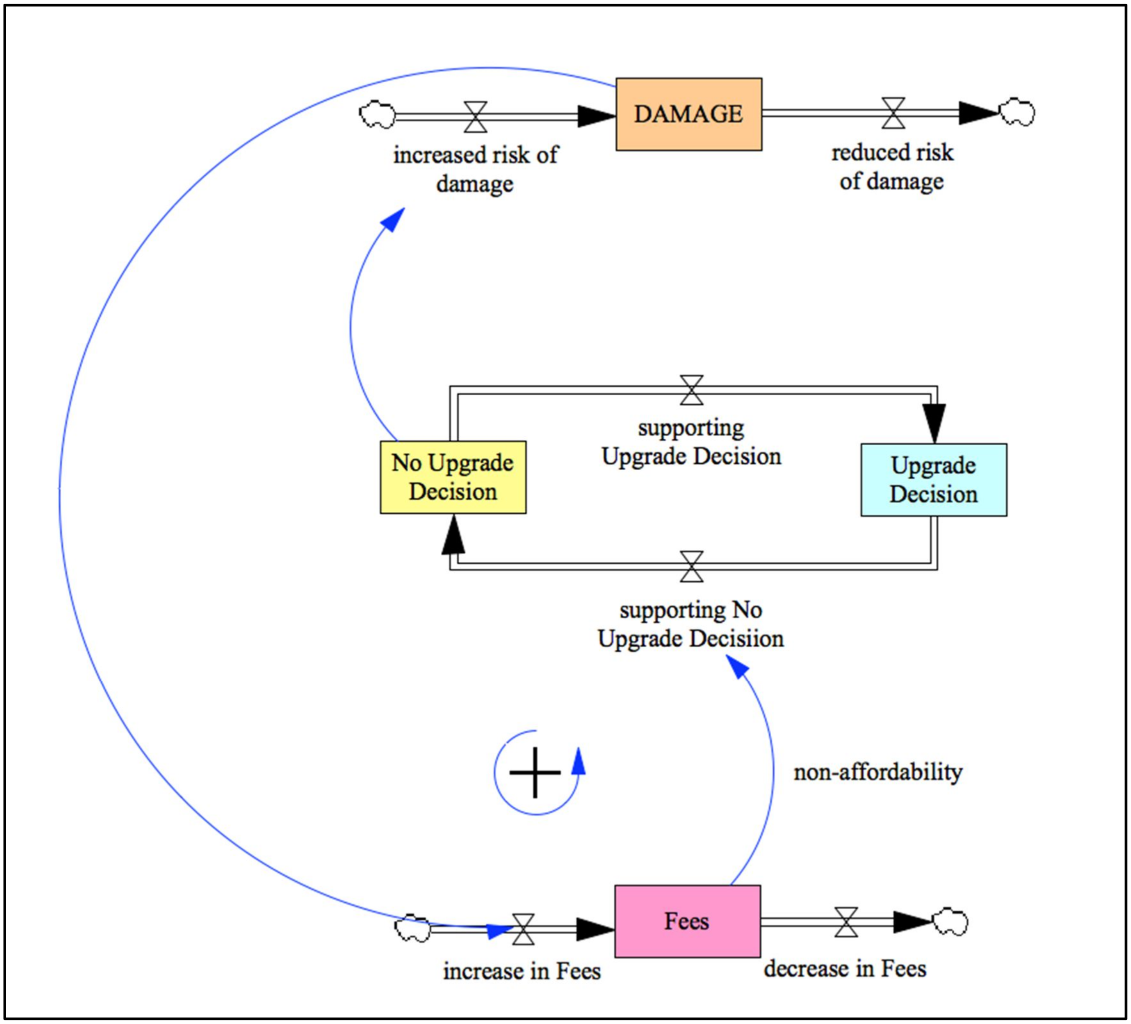

Fig. (7-13): Stock-and-flow diagram of the infrastructure and economics layers showing only the reinforcing loop.

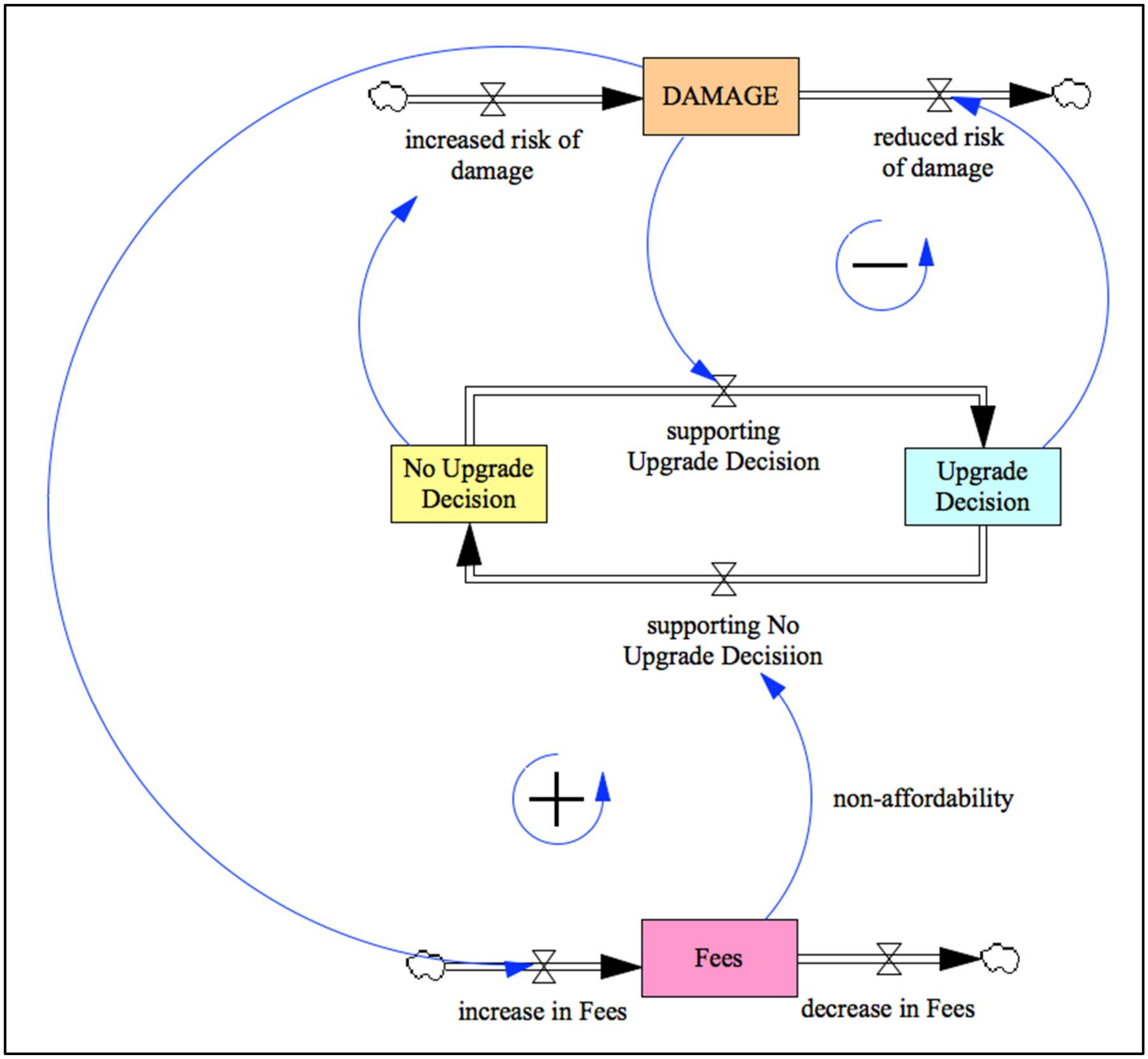

Fig. (7-14): Stock-and-flow diagram of the infrastructure and economic layers with the reinforcing and balancing loops.

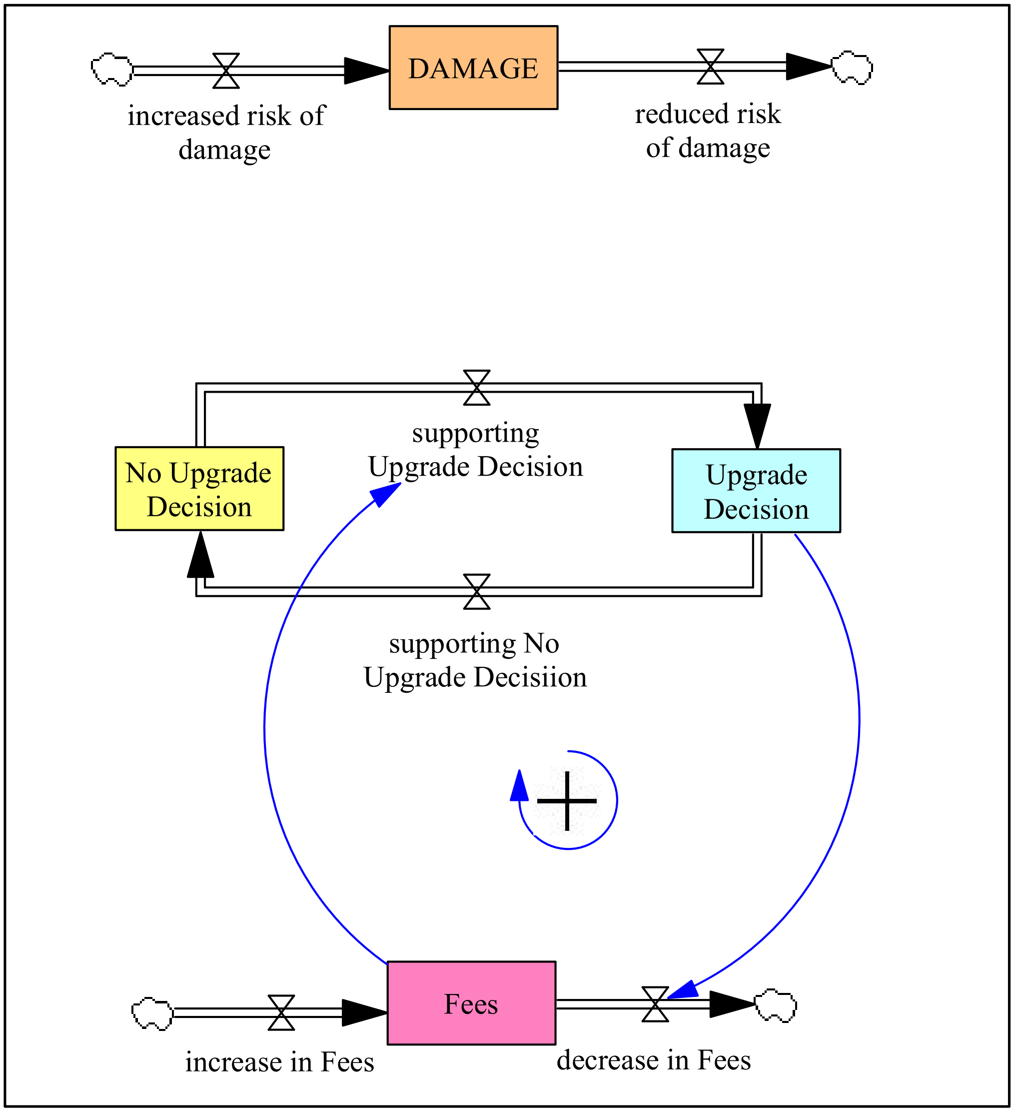

Fig. (7-15): Stock-and-flow diagram of the infrastructure and economics layers showing only the reinforcing loop.

We are now ready to add the social cohesion layer. In Figure (7-16), we show, at the top of the diagram, a social cohesion stock, that quantifies the degree of social cohesion in the community. We can use the linear systems theory constructs, with

$$\text{social cohesion } stock = \sum_i c_{i,\text{member}}\, v_{\text{member}} \qquad (7\text{-}15)$$

in which $c_{i,\text{member}} v_{\text{member}}$ represents the contribution of homeowner i to the community in the form of active membership. The flow into the social cohesion (SC) stock has a valve labeled building SC. Continuing with the linear systems theory constructs,

$$\text{building SC flow} = k \sum_i r_{\text{community},i} + \text{other influences} \tag{7-16}$$

in which $r_{\text{community},i}$ are the resources offered by the community to homeowner i, and the coefficient k relates the sum of these resources to the rate of flow. Figure (7-15) also show the one and only auxiliary variable shown in our stock and flow diagram, the community protective measure. This is a binary variable indicating the presence or lack of a measure. The arrows pointing towards this variable shows that both social cohesion and high levels of expected damage would tend to promote the construction of the measure. The social cohesion effect is represented by the exponents x_i in the expression for the homeowner's utility

$$U_i = U_{i,\text{individual}}^{1-x_i} U_{\text{community}}^{x_i} \tag{5-16}$$

and the expected damage effect is represented by both utilities, $U_{i,\text{individual}}$ and $U_{\text{community}}$ in the expression above. The status of the community protective measure is determined by the sum of the above.

One of the arrows emanating from the community protective measure variable indicates that the presence of a measure will lead to reduced risk of damage; this is quantified by the system value of the measure with respect to upgraded and non-upgraded residences described earlier in this chapter:

$$v_{\text{measure (upgrade)}} = \Delta \text{ER}_{\text{upgrade}} \tag{7-5}$$

$$v_{\text{measure (no upgrade)}} = \Delta ER_{\text{no upgrade}}$$

Another arrow indicates an increase in the fees, since the cost of the measure is passed to the homeowners through the insurer fees. This increase is determined by the computational ABM. Finally, there is an arrow indicating an increase in social cohesion because of the symbolic nature of a community-sponsored measure representing the cohesiveness of a community. This influence would be included on the right side of equation (7-16).

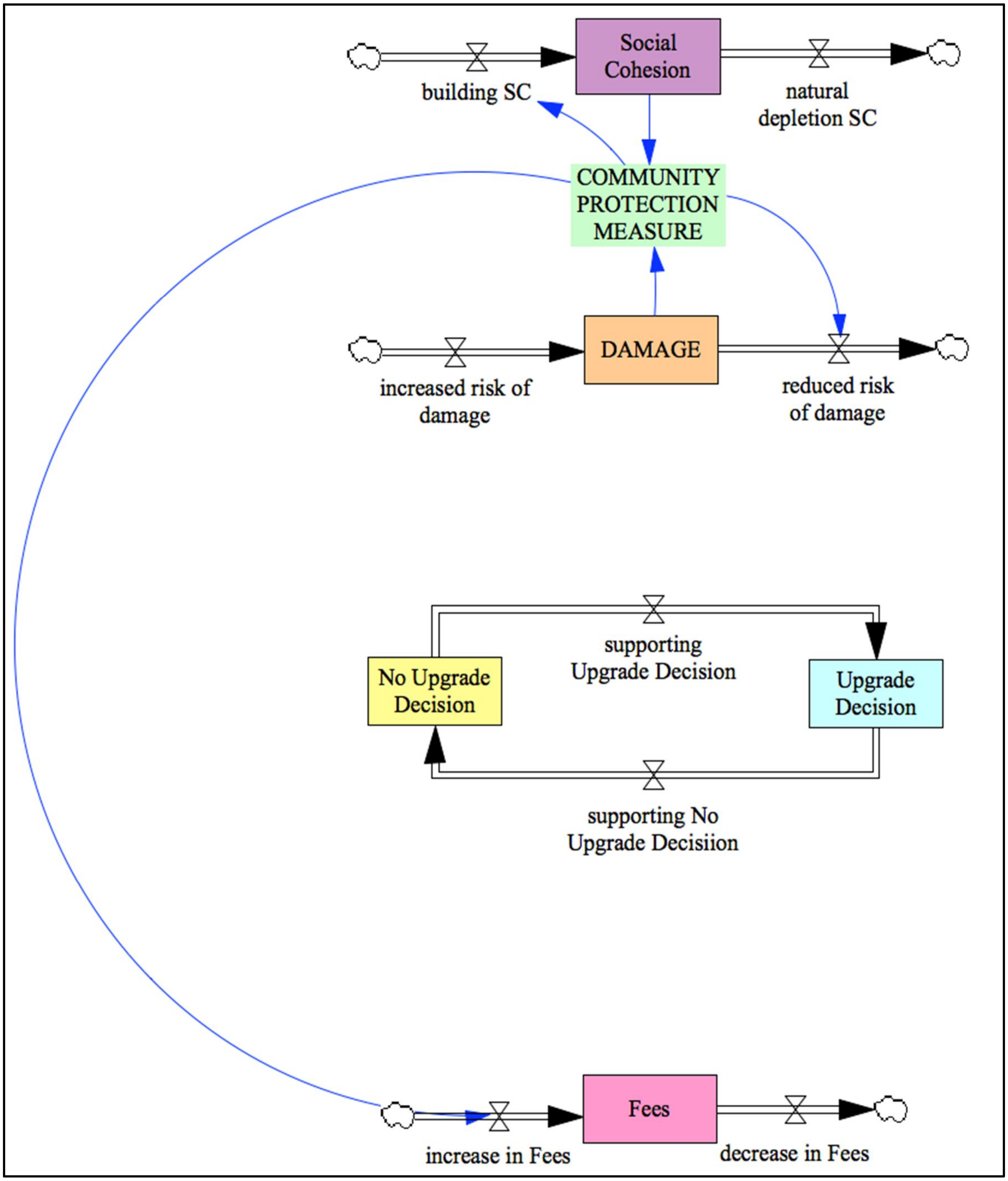

Fig. (7-16): Stock-and-flow diagram showing the addition of the social cohesion layer.

The complete stock-and-flow diagram showing all of the simplified relationships for the social cohesion, infrastructure and economic layers is shown in Figure (7-17).

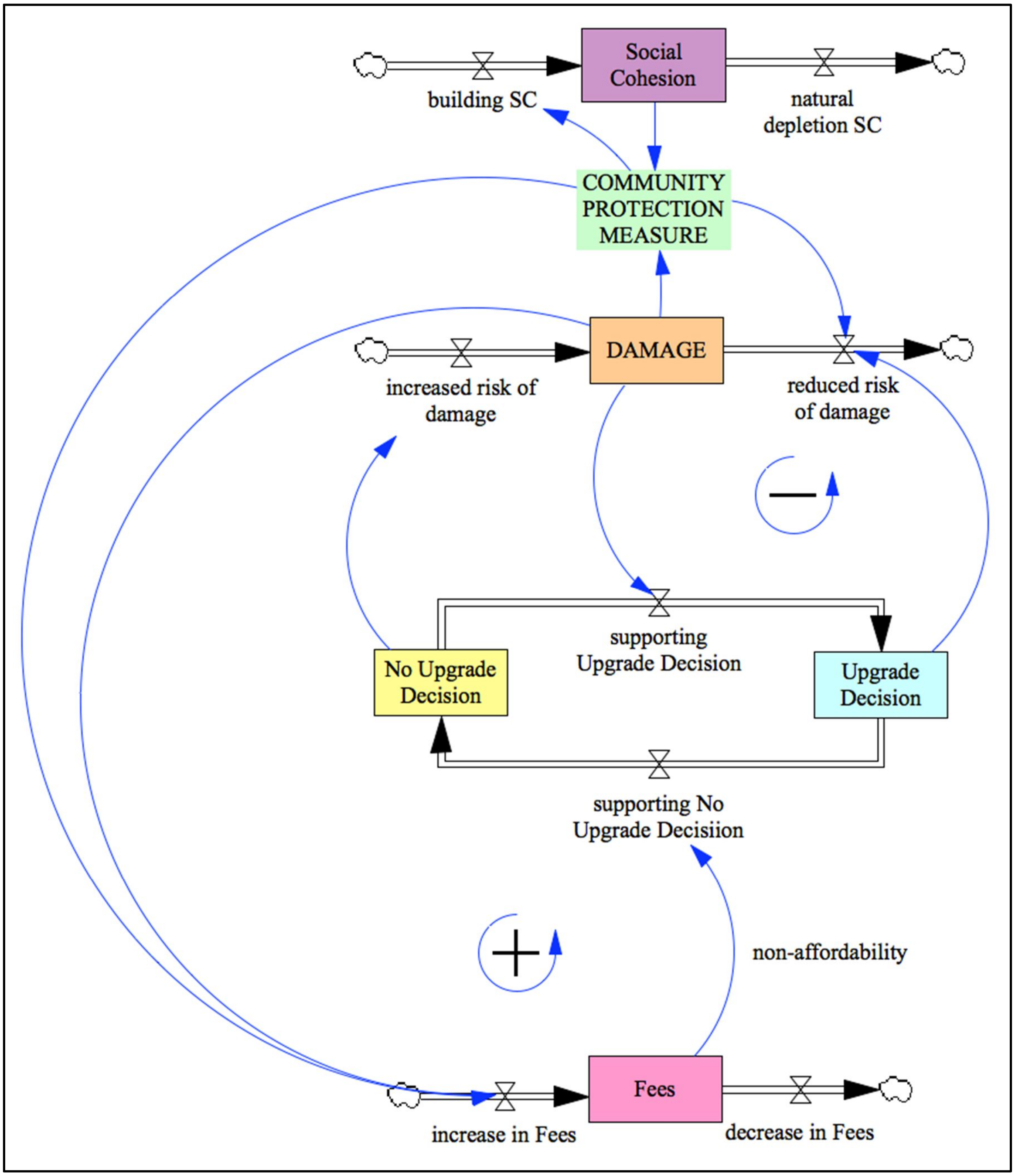

Fig. (7-17): Complete stock-and-flow diagram for community resilience showing, in a simplified representation, the social cohesion layer at the top, the infrastructure layer in the middle and the economic layer at the bottom.

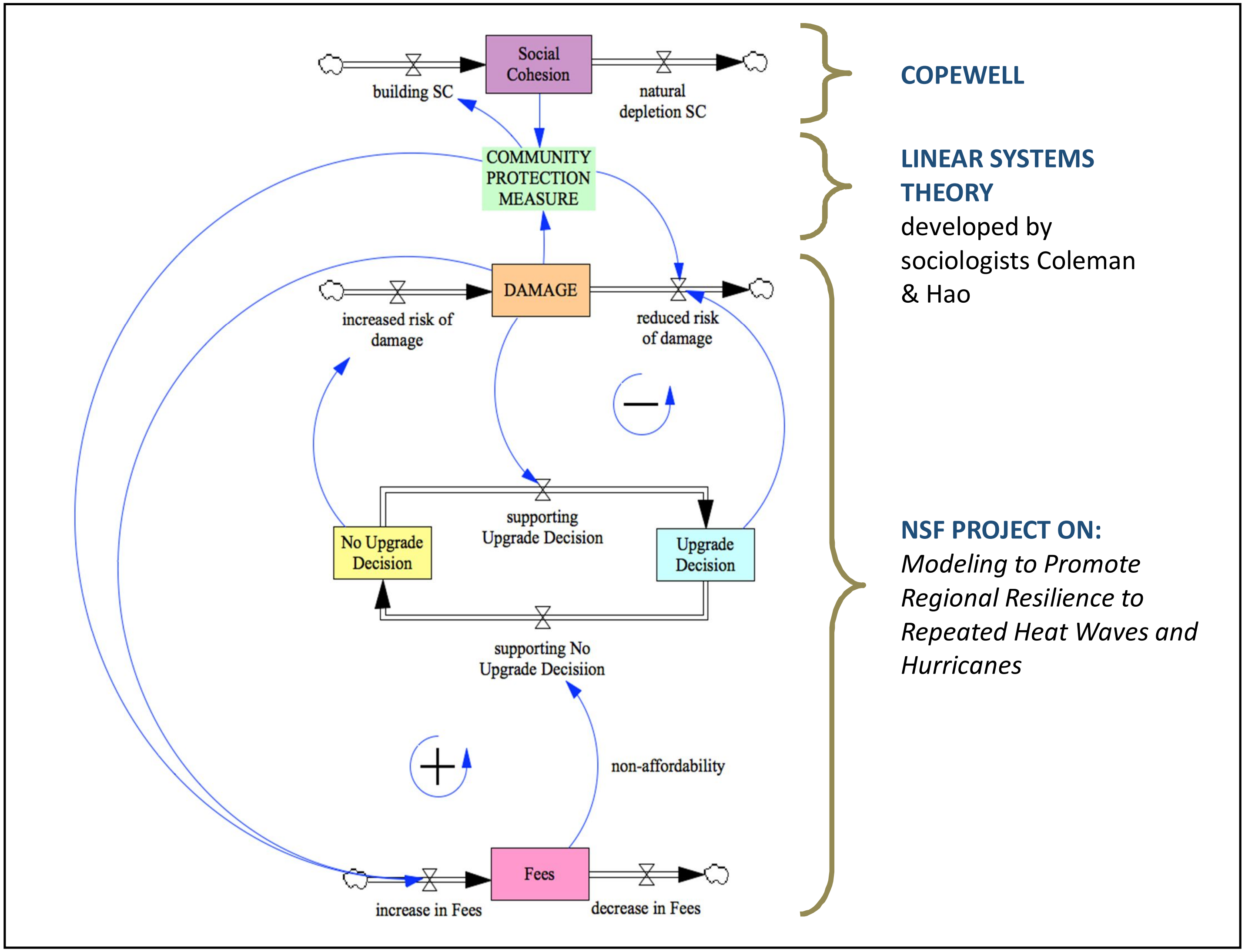

Fig. (7-18): Complete stock-and-flow diagram for community resilience showing, in a simplified representation, the social cohesion layer at the top, the infrastructure layer in the middle and the economic layer at the bottom.

It is noted that in a separate CDC-funded effort, known as the COPEWELL project, a stock-and-flow model has been being developed for community resilience. Social cohesion is one of the stocks of this model and the definition of social cohesion is compatible with that used herein. Hence, in the future, it will be possible to link the COPEWELL system dynamics model with the ABM model developed in Chapter 5 and the Linear Systems Analysis as explained earlier in the present chapter. This is illustrated in in Figure (7-18). COPEWELL also includes wider measures of disaster that include sociological definitions of community dysfunction, as mentioned earlier.

Chapter 8

Concluding Remarks

8.1 Summary and Conclusion

In this thesis we have shown how a systems approach can be used to describe infrastructure-building scenarios in flood-prone coastal communities. We have shown how short-term decisions at the individual homeowner level can interact with long-term decisions at the community level. We showed how several systems methods can provide understanding into different aspects of community resilience. UML was particularly useful in diagramming the complex time-evolution of processes associated with damage, repair and upgrade that interact at the homeowner and community levels. The behaviors that were conceptually described by the UML were programmed into economic-driven action in an ABM. The principal actors were a not-for-profit insurer, community government, and individual homeowners who were also members of the community. While we assumed that the insurer would cover all costs associated with damage from flood events, we also assigned monetary values to risk aversion and to the cost of suffering associated with disaster recovery. We were able to derive mathematical relationships for the key economic quantities that govern individual and insurer decisions, including the fees to set for insurance, discounts to offer for those that upgrade their homes, and the decisions for the homeowners regarding residential upgrades and the financial support of a community flood-mitigation measure. We were also able to describe the emergent economic behaviors of the actors through a sequence of level-plots.

It is shown how linear systems theory from sociology [Coleman and Hao 1987] can be used to quantify the interactions between community members and the community as a whole in terms of exchanges of resource contributions. Three types of exchanges are shown using closely interacting layers. The top layer is related to the notion of social cohesion; the second focused on economics at the individual and community levels; and the third layer is purely in terms of infrastructure capabilities, again at the individual household and community levels. While most of the analyses of resource exchanges require the use of the computational ABM, it was shown how a conceptual SD model can be used to illustrate the feedback mechanisms acting through all three layers in a format that can be used to communicate more effectively with policy makers and community representatives. This combination of approaches brings greater transparency to the multiple dimensions of human interactions in building community resilience.

We also developed a model for rapidly assessing hurricane-associated surge risks in the mid-Atlantic. We built on previous work by Irish et al. (2009) to construct a mathematical model of surge risk, and applied the maximum likelihood principle to estimate the parameters. This model was trained and cross-validated using a set of 1,380 surge heights (U.S. Army Corps of Engineers, 2015) that were generated by the ADCIRC surge model and SWAN wave model. We were able to rapidly compute flood elevation predictions from storms characteristics using only a few parameters: hurricane landfall location (x_o), heading direction (θ), central pressure deficit (ΔP), radius of maximum winds (R_{max}), and translational speed (V_t). The accuracy was suitable for classification applications in which storms with high risk potential would be selected for future study with more computationally intensive models.

Some of the key results of the computational agent-based model are as follows:

a. The model calculates the expected costs associated with storm resilience and recovery in terms of the probability distributions of the intensity of the storms, damage, at different levels, given the storm intensity, protective capabilities of residential upgrades and community measures, and homeowners' costs of suffering and risk-aversion.
b. The model calculates the indifference curve for the residents of a coastal community located in SFHA. This curve shows the potential behavior of the residents with regard to affordability and willingness to upgrade.
c. The model computes optimal flood insurance premium rates for the community residents that minimizes costs, and leads to zero net profit or loss for the insurer.
d. The model determines the proportion of the homeowners who will upgrade their properties, and determines changes in this proportion that will occur if the community decides to build a measure.

e. The behavior of the agents is shown through multiple plots. This visual representation can be used to identify trends associated with the costs and effectiveness of upgrades and community measures and can also be used to analyze voting patterns that may influence the decision to build or not build a community measure in a manner that is not optimal for the community.

8.2 Recommendations for Future Research

In this section, a list of recommended future work is proposed to build on the work herein.

The storm surge prediction model, can be improved as follows:

- Model can be extended to predict surge levels in coastal bay areas.

- An interpolating feature can be added to so that the model can provide predictions at locations other than the specific stations of the NACCS study.

- Near-miss analysis. It is important to be able to predict the probability that an approaching storm makes landfall or bypasses the coasts; and predict the resulting surge elevations from each scenario.

The computational ABM can be extended to include:

- Different flood zones (geographically defined risk levels) with varying flood insurance premium rates, probabilities of damage, costs of repair, and costs of suffering.

- Different degrees of resiliency of each structure against a flood event in the same flood zone, including aging of the properties over time.

- Different levels of upgrade in the houses with corresponding insurance discount rates.

- Move and relocation strategies for individual homeowners or the entire community to move out of the flood zone (e.g., never move, move after damaged twice, etc.)

- Alternatives for the measure type, size, location, and flood protection level.

- Costs associated with various effects of each measure option on individual properties and the entire community (e.g., access to the beach, potential blockage of scenic views)

- A graphic user-interface (GUI) with controller buttons or sliders to change the model input values for more comprehensible visualization of the characteristics of the system, including the interactions between system components.

- Additional scenarios of storm damage and more options for the cost of repair.

- More complicated scenarios for grant applications that are needed to build federally sponsored measures. Different types of grants can be considered for repair of damaged properties after a flood event. For instance, a community may receive extra repair funds after a flood event if the president of the U.S. declares it as a major disaster. These funds include individual assistance and public assistance, though these funds often are in the form of interest-bearing loans.

- More realistic distribution functions for affordability and cost of risk (risk aversion) that are based on socio-economic studies.

- Bayes theory can be used to modify probabilities after each storm event. In the current model, we have assumed the homeowners have perfect knowledge of the probabilities and know the exact outcome of their decisions. In reality however, the probabilities will evolve in a process that resembles a learning curve. The initial homeowner probabilities are approximate and get updated after each storm as the homeowners observe the damage arising from each storm.

- Near misses. An important application of the Bayes extension described above is in modeling homeowner decisions after a near miss event. Under this condition, homeowners would tend to underestimate the hazards of future storms, and this would be reflected by a lowering of the homeowners' probabilities of damage.

- A reinsurance program to protect the insurer against severe losses. Given the extents of the risks and costs of major disasters, reinsurance programs can help the flood insurance companies remain solvent after such hurricane events.

- Non-stationarity (e.g., climate change effects). The current study is conducted using stationary stochastic processes in which the joint probability distributions do not change over time; the value of storm parameters such as severity and probability of occurance remain constant in time. Future studies can take account of increasing probabilities of severe events that are due to climate change.

- Catastrophic losses. The ABM can include very large, unexpected events that can overwhelm standard upgrades and flood control measures, resulting in catastrophic losses for every homeowner in the community.

- For-profit insurer and subsidizing insurer. The model can be modified to include these two cases to account for the ability of homeowners to pay for insurance. With such a model, it will be possible to examine the effects of profits/subsidies on the solvency of the insurer, the upgrade decisions made by the community residents, votes for or against addition of a community flood control measure, and ultimately, their effects on flood resiliency of the entire coastal community.

- Negative cost of risk. In this study we have only considered non-negative values for the cost of risk. The probability density function of the cost of risk used as an input to the ABM can be modified to include negative values of cost of risk for homeowners who do not understand or underestimate the risk of damage.

- Visualization over time of the system dynamics model. The ABM can be modified to keep track of and visualize the changes in the stocks and flows in the system dynamics model over time (e.g. the number of homeowners who plan to upgrade). The current model only shows the current state of the stocks and does not give comparisons with the previous decisions made by the agents.

Appendix A

NACCS Synthetic TC Parameters

Table (A-1) provides a list of 348 of the total 1,050 synthetic tropical storms (TCs) that were developed for the NACCS study area. The storm track location, or the landfall location (for the landfalling storms), of these selected 348 synthetic storms are in the coastal regions of FEMA sub-region III (which includes DC, DE, MD, PA, VA, WV). Storm parameters assigned to each cyclone are heading direction (θ), central pressure deficit (ΔP), radius of maximum winds (R_{max}), and translational speed (V_t). Table (A-1) is adopted from Appendix C of the "Coastal storm hazards from Virginia to Maine: ERDC/CHL TR-15-5" report of the NACCS study [NACCS 2015].

Table (A-1): NACCS synthetic TC parameters [NACCS 2015].

NACCS Synthetic Tropical Cyclone ID	NACCS Sub-region	Master Track ID	θ (deg)	ΔP (hPa)	R_{max} (km)	V_t (km/h)
1	3	1	-60	88	39	18
2	3	1	-60	78	108	29
3	3	1	-60	68	62	42
4	3	1	-60	58	47	32
5	3	1	-60	48	64	12
6	3	1	-60	38	72	19
7	3	1	-60	28	26	39
8	3	2	-60	88	114	25
9	3	2	-60	78	51	30
10	3	2	-60	68	26	31
11	3	2	-60	58	37	12
12	3	2	-60	48	77	44
13	3	2	-60	38	72	13
14	3	2	-60	28	39	39
15	3	3	-60	88	105	24
16	3	3	-60	78	50	30
17	3	3	-60	68	39	12
18	3	3	-60	58	26	29
19	3	3	-60	48	82	44
20	3	3	-60	38	68	15
21	3	3	-60	28	42	40
22	3	4	-60	88	50	40
23	3	4	-60	78	51	29
24	3	4	-60	68	107	26
25	3	4	-60	58	65	12
26	3	4	-60	48	28	34
27	3	4	-60	38	37	13
28	3	4	-60	28	75	38
29	3	5	-60	88	77	37
30	3	5	-60	78	35	26
31	3	5	-60	68	62	12
32	3	5	-60	58	109	25
33	3	5	-60	48	49	25
34	3	5	-60	38	58	40
35	3	5	-60	28	25	35
36	3	6	-60	88	72	31
37	3	6	-60	78	38	27
38	3	6	-60	68	53	35

NACCS Synthetic Tropical Cyclone ID	NACCS Sub-region	Master Track ID	θ (deg)	ΔP (hPa)	R_{max} (km)	V_t (km/h)
39	3	6	-60	58	105	28
40	3	6	-60	48	64	14
41	3	6	-60	38	25	28
42	3	6	-60	28	61	46
43	3	7	-60	88	50	37
44	3	7	-60	78	78	12
45	3	7	-60	68	104	35
46	3	7	-60	58	41	12
47	3	7	-60	48	25	31
48	3	7	-60	38	48	20
49	3	7	-60	28	71	33
50	3	8	-60	88	47	18
51	3	8	-60	78	75	40
52	3	8	-60	68	104	21
53	3	8	-60	58	41	39
54	3	8	-60	48	67	36
55	3	8	-60	38	25	19
56	3	8	-60	28	58	13
57	3	25	-40	88	53	20
58	3	25	-40	78	105	21
59	3	25	-40	68	29	22
60	3	25	-40	58	73	41
61	3	25	-40	48	51	40
62	3	25	-40	38	38	36
63	3	25	-40	28	65	12
64	3	26	-40	88	54	30
65	3	26	-40	78	104	30
66	3	26	-40	68	37	12
67	3	26	-40	58	29	38
68	3	26	-40	48	80	13
69	3	26	-40	38	63	47
70	3	26	-40	28	50	23
71	3	27	-40	88	44	24
72	3	27	-40	78	66	45
73	3	27	-40	68	117	25
74	3	27	-40	58	52	17
75	3	27	-40	48	26	20
76	3	27	-40	38	39	41
77	3	27	-40	28	74	23

NACCS Synthetic Tropical Cyclone ID	NACCS Sub-region	Master Track ID	θ (deg)	ΔP (hPa)	R_{max} (km)	V_t (km/h)
78	3	28	-40	88	69	43
79	3	28	-40	78	53	16
80	3	28	-40	68	37	42
81	3	28	-40	58	103	23
82	3	28	-40	48	29	19
83	3	28	-40	38	62	38
84	3	28	-40	28	60	25
85	3	29	-40	88	53	35
86	3	29	-40	78	79	22
87	3	29	-40	68	32	22
88	3	29	-40	58	105	28
89	3	29	-40	48	55	12
90	3	29	-40	38	31	47
91	3	29	-40	28	59	39
92	3	30	-40	88	53	21
93	3	30	-40	78	42	22
94	3	30	-40	68	115	40
95	3	30	-40	58	25	33
96	3	30	-40	48	83	24
97	3	30	-40	38	50	45
98	3	30	-40	28	46	13
99	3	31	-40	88	65	16
100	3	31	-40	78	54	44
101	3	31	-40	68	104	31
102	3	31	-40	58	44	17
103	3	31	-40	48	27	32
104	3	31	-40	38	46	25
105	3	31	-40	28	74	21
106	3	50	-20	98	66	38
107	3	50	-20	88	76	12
108	3	50	-20	78	42	21
109	3	50	-20	68	113	32
110	3	50	-20	58	25	23
111	3	50	-20	48	37	49
112	3	50	-20	38	62	30
113	3	51	-20	98	48	26
114	3	51	-20	88	117	29
115	3	51	-20	78	68	42
116	3	51	-20	68	47	24

NACCS Synthetic Tropical Cyclone ID	NACCS Sub-region	Master Track ID	θ (deg)	ΔP (hPa)	R_{max} (km)	V_t (km/h)
117	3	51	-20	58	72	12
118	3	51	-20	48	33	41
119	3	51	-20	38	31	12
120	3	52	-20	98	63	28
121	3	52	-20	88	38	22
122	3	52	-20	78	115	26
123	3	52	-20	68	70	38
124	3	52	-20	58	25	25
125	3	52	-20	48	44	43
126	3	52	-20	38	63	12
127	3	53	-20	98	59	19
128	3	53	-20	88	116	33
129	3	53	-20	78	27	36
130	3	53	-20	68	37	20
131	3	53	-20	58	56	46
132	3	53	-20	48	75	21
133	3	53	-20	38	45	20
134	3	54	-20	98	49	33
135	3	54	-20	88	100	17
136	3	54	-20	78	87	44
137	3	54	-20	68	28	20
138	3	54	-20	58	50	12
139	3	54	-20	48	65	27
140	3	54	-20	38	38	46
141	3	72	0	88	42	31
142	3	72	0	83	53	12
143	3	72	0	78	77	35
144	3	72	0	73	133	26
145	3	72	0	68	40	16
146	3	72	0	63	26	13
147	3	72	0	58	29	38
148	3	72	0	53	55	21
149	3	72	0	48	51	48
150	3	72	0	43	71	15
151	3	72	0	38	59	39
152	3	72	0	33	98	35
153	3	72	0	28	33	20
154	3	73	0	88	53	27
155	3	73	0	83	39	12

NACCS Synthetic Tropical Cyclone ID	NACCS Sub-region	Master Track ID	θ (deg)	ΔP (hPa)	R_{max} (km)	V_t (km/h)
156	3	73	0	78	145	20
157	3	73	0	73	49	46
158	3	73	0	68	79	29
159	3	73	0	63	27	28
160	3	73	0	58	42	12
161	3	73	0	53	87	12
162	3	73	0	48	76	42
163	3	73	0	43	39	33
164	3	73	0	38	25	13
165	3	73	0	33	50	12
166	3	73	0	28	83	24
167	3	74	0	88	93	28
168	3	74	0	83	59	31
169	3	74	0	78	41	31
170	3	74	0	73	64	12
171	3	74	0	68	40	16
172	3	74	0	63	25	25
173	3	74	0	58	69	47
174	3	74	0	53	114	25
175	3	74	0	48	78	21
176	3	74	0	43	45	36
177	3	74	0	38	67	26
178	3	74	0	33	25	53
179	3	74	0	28	53	16
180	3	75	0	88	51	24
181	3	75	0	83	29	38
182	3	75	0	78	140	32
183	3	75	0	73	64	25
184	3	75	0	68	59	51
185	3	75	0	63	73	12
186	3	75	0	58	38	14
187	3	75	0	53	42	40
188	3	75	0	48	25	25
189	3	75	0	43	52	22
190	3	75	0	38	92	32
191	3	75	0	33	71	21
192	3	75	0	28	39	36
193	3	107	20	88	63	29
194	3	107	20	83	33	26

NACCS Synthetic Tropical Cyclone ID	NACCS Sub-region	Master Track ID	θ (deg)	ΔP (hPa)	R_{max} (km)	V_t (km/h)
195	3	107	20	78	140	29
196	3	107	20	73	71	49
197	3	107	20	68	60	12
198	3	107	20	63	56	12
199	3	107	20	58	73	28
200	3	107	20	53	31	46
201	3	107	20	48	35	48
202	3	107	20	43	88	21
203	3	107	20	38	25	17
204	3	107	20	33	41	22
205	3	107	20	28	59	35
206	3	108	20	88	59	33
207	3	108	20	83	104	35
208	3	108	20	78	46	24
209	3	108	20	73	53	12
210	3	108	20	68	31	29
211	3	108	20	63	47	37
212	3	108	20	58	142	13
213	3	108	20	53	69	17
214	3	108	20	48	43	59
215	3	108	20	43	27	12
216	3	108	20	38	73	34
217	3	108	20	33	25	27
218	3	108	20	28	55	33
219	3	109	20	88	40	27
220	3	109	20	83	75	18
221	3	109	20	78	106	50
222	3	109	20	73	63	36
223	3	109	20	68	135	21
224	3	109	20	63	25	38
225	3	109	20	58	48	12
226	3	109	20	53	54	27
227	3	109	20	48	38	45
228	3	109	20	43	34	33
229	3	109	20	38	79	34
230	3	109	20	33	31	12
231	3	109	20	28	40	29
232	3	110	20	88	54	15
233	3	110	20	83	140	18

NACCS Synthetic Tropical Cyclone ID	NACCS Sub-region	Master Track ID	θ (deg)	ΔP (hPa)	R_{max} (km)	V_t (km/h)
234	3	110	20	78	66	25
235	3	110	20	73	56	44
236	3	110	20	68	79	19
237	3	110	20	63	29	18
238	3	110	20	58	33	44
239	3	110	20	53	33	19
240	3	110	20	48	51	33
241	3	110	20	43	100	35
242	3	110	20	38	25	34
243	3	110	20	33	74	12
244	3	110	20	28	46	29
245	3	111	20	88	44	18
246	3	111	20	83	104	19
247	3	111	20	78	25	42
248	3	111	20	73	95	36
249	3	111	20	68	55	19
250	3	111	20	63	71	23
251	3	111	20	58	86	52
252	3	111	20	53	49	45
253	3	111	20	48	67	12
254	3	111	20	43	25	12
255	3	111	20	38	41	29
256	3	111	20	33	32	29
257	3	111	20	28	71	27
258	3	112	20	88	67	23
259	3	112	20	83	85	16
260	3	112	20	78	44	16
261	3	112	20	73	62	49
262	3	112	20	68	44	38
263	3	112	20	63	137	33
264	3	112	20	58	28	31
265	3	112	20	53	27	26
266	3	112	20	48	47	28
267	3	112	20	43	79	27
268	3	112	20	38	60	12
269	3	112	20	33	38	49
270	3	112	20	28	45	19
271	3	125	40	98	76	28
272	3	125	40	93	51	23

NACCS Synthetic Tropical Cyclone ID	NACCS Sub-region	Master Track ID	θ (deg)	ΔP (hPa)	R_{max} (km)	V_t (km/h)
273	3	125	40	88	68	46
274	3	125	40	83	89	20
275	3	125	40	78	139	30
276	3	125	40	73	26	20
277	3	125	40	68	55	12
278	3	125	40	63	41	28
279	3	125	40	58	35	35
280	3	125	40	53	25	34
281	3	125	40	48	61	35
282	3	125	40	43	79	21
283	3	125	40	38	47	27
284	3	126	40	98	92	33
285	3	126	40	93	45	35
286	3	126	40	88	34	27
287	3	126	40	83	125	23
288	3	126	40	78	62	26
289	3	126	40	73	61	30
290	3	126	40	68	74	15
291	3	126	40	63	25	31
292	3	126	40	58	25	31
293	3	126	40	53	83	44
294	3	126	40	48	42	59
295	3	126	40	43	35	12
296	3	126	40	38	63	47
297	3	127	40	98	68	20
298	3	127	40	93	132	22
299	3	127	40	88	55	37
300	3	127	40	83	50	12
301	3	127	40	78	40	50
302	3	127	40	73	30	27
303	3	127	40	68	98	31
304	3	127	40	63	60	17
305	3	127	40	58	90	21
306	3	127	40	53	34	13
307	3	127	40	48	43	12
308	3	127	40	43	38	21
309	3	127	40	38	26	40
310	3	128	40	98	92	40
311	3	128	40	93	44	27

NACCS Synthetic Tropical Cyclone ID	NACCS Sub-region	Master Track ID	θ (deg)	ΔP (hPa)	R_{max} (km)	V_t (km/h)
312	3	128	40	88	60	42
313	3	128	40	83	75	18
314	3	128	40	78	67	39
315	3	128	40	73	126	30
316	3	128	40	68	62	12
317	3	128	40	63	30	39
318	3	128	40	58	26	42
319	3	128	40	53	58	51
320	3	128	40	48	25	15
321	3	128	40	43	39	17
322	3	128	40	38	73	26
323	3	129	40	98	61	27
324	3	129	40	93	71	46
325	3	129	40	88	121	22
326	3	129	40	83	46	22
327	3	129	40	78	25	34
328	3	129	40	73	70	15
329	3	129	40	68	50	54
330	3	129	40	63	42	12
331	3	129	40	58	48	38
332	3	129	40	53	27	16
333	3	129	40	48	88	34
334	3	129	40	43	64	33
335	3	129	40	38	57	12
336	3	130	40	98	104	12
337	3	130	40	93	87	31
338	3	130	40	88	46	12
339	3	130	40	83	40	25
340	3	130	40	78	61	36
341	3	130	40	73	79	12
342	3	130	40	68	28	35
343	3	130	40	63	103	31
344	3	130	40	58	56	19
345	3	130	40	53	42	33
346	3	130	40	48	45	57
347	3	130	40	43	53	32
348	3	130	40	38	26	14

Bibliography

- Arrow, K. J. and Hahn, F. H., (1971). "General Competitive Analysis". San Francisco: Holden-Day.
- Benjamin, J. R. and Cornell, C. A., (2014). "Probability, Statistics, and Decision for Civil Engineers". Dover Books on Engineering.
- Birkland, T. A., (1997). "After disaster: agenda setting, public policy, and focusing events". Georgetown University Press, Washington, DC.
- Blake, E. S., C. W. Landsea, and Gibney, E. J., (2011). "The deadliest, costliest, and most intense United States tropical cyclones from 1851 to 2010 (and other frequently requested hurricane facts)". NOAA Technical Memorandum NWS NHC-6. Miami, FL: National Hurricane Center National Weather Service, National Oceanic and Atmospheric Administration.
- Booch, Gary, et. al, (2005). "The Unified Modeling Language User Guide". 496p.
- Burkett, V. R., and Davidson, M. A., (2012). "Coastal impacts, adaptation and vulnerability: A technical input to the 2012 National Climate Assessment".

Cooperative Report to the 2013 National Climate Assessment, 150. Washington, DC: Island Press.

- Cialone M. A., Massey, T. C., Anderson, M. E., Grzegorzewski, A. S., Jensen, R. E., Cialone, A., Mark, D. J., Peavey, K. C., Gunkel, B. L., McAlpin, T. O., Nadal-Caraballo, N. C., Melby, J. A., and Ratcliff. J. J., (2015). “North Atlantic Coast Comprehensive Study (NACCS) Coastal Storm Model Simulations: Waves and Water Levels”. ERDC/CHL TR-15-14. Vicksburg, MS: U.S. Army Engineer Research and Development Center, 252p.
- Church, J. A., and White, N. J., (2011). “Sea-level rise from the late 19th to the early 21st century”. Surveys in Geophysics 32(4–5), pp. 585–602.
- Coleman, J. S., and Hao, L., (1989). “Linear Systems Analysis: Macrolevel Analysis with Microlevel Data”. Sociological Methodology. Vol. 19, pp. 395-422.
- Clemen, R.T., and Reilly, T., (2000). “Making Hard Decisions with Decision Tools Suite”. Boston, Massachusetts: Duxbury Press.
- Dixon, L., Clancy, N., Seabury, S., and Overton, A., (2006). “The National Flood Insurance Program’s Market Penetration Rate: Estimates and Policy Implications (AIR Evaluation of NFIP Report)”. American Institutes for Research, Washington DC. 140p.
- Forrester, J. W., (2009). “Learning through system dynamics as preparation for the 21st century”. Acton, MA: Creative Learning Exchange.
- Good, P. I., (2001). “Resampling methods: A practical guide to data analysis”. 3rd ed. Berlin, Germany: Birkhauser.

- Haan, C. T., (2002). "Statistical methods in hydrology". 2nd ed., Wiley Series in Probability and Statistics, New York: John Wiley and Sons, Inc.
- Hayat, B., and Moore, R., (2015). "Addressing Affordability and Long-Term Resiliency through the National Flood Insurance Program". Environmental Law Reporter, Washington DC, 12p.
- Hawe, G. I., et al., (2012). "Agent-Based Simulation for Large-Scale Emergency Response: A Survey of Usage and Implementation". ACM Computing Surveys. Volume 45, Issue 1, p. 8:1.
- Hawkes, P. J., Gouldby, B. R., Tawn, J. A., and Owen, M. W., (2002). "The joint probability of waves and water levels in coastal engineering design". Journal of Hydraulic Research 40(3), pp 241–251.
- Hawkes, P., and Svensson, C., (2005). "Joint probability: Dependence mapping and best practice". Technical report on dependence mapping, HR Wallingford SR Report SR623. United Kingdom: Oxfordshire.
- Hirsch, G. B., Levine, R., and Miller, R. L., (2007). "Using system dynamics modeling to understand the impact of social change initiatives". American Journal of Community Psychology, 39(3-4), 239-253. doi: 10.1007/s10464-007-9114-3.
- Holland G. J., (1980). "An Analytic Model of the Wind and Pressure Profiles in Hurricanes". Monthly Weather Review. Volume 108:1212–1218.
- Hovmand, P. S., (2013). "Community Based System Dynamics". New York: Springer.
- James, G., Tibshirani, R., and Hastie, T., (2013). "An Introduction to Statistical Learning". Springer, 441 p.

- King, R. O., (2005). "CRS Report for Congress. Federal Flood Insurance: The Repetitive Loss Problem". Congressional Research Service, The Library of Congress, 45p.
- Mabry, P. L., Olster, D. H., Morgan, G. D., and Abrams, D. B., (2008). "Interdisciplinarity and systems science to improve population health: a view from the NIH Office of Behavioral and Social Sciences Research". American journal of preventive medicine, 35(2), S211-S224.
- Meadows, D. H., (1999). "Leverage points: Places to intervene is a system." Heartland, VT: The Sustainability Institute, 21p.
- Nadal-Caraballo, N. C., Melby J. A., Gonzalez, V. M., and Cox, A. T., (2015). "Coastal Storm Hazards from Virginia to Main", North Atlantic Coast Comprehensive Study (NACCS), USACE, ERDC/CHL TR-15-5, 221p.
- Nadal-Caraballo, N. C., and Melby, J. A., (2014). "North Atlantic Coast Comprehensive Study – Phase I: Statistical analysis of historical extreme water levels with sea level change." ERDC/CHL TR-14-7. Vicksburg, MS: U.S. Army Engineer Research and Development Center, 125p.
- National Oceanographic and Atmospheric Administration (NOAA), (2012). "Global sea level rise scenarios for the U.S. National Climate Assessment. NOAA Technical Report OAR CPO-1". Silver Spring, MD: Climate Program Office.
- National Oceanic & Atmospheric Administration (NOAA) website: http://oceanservice.noaa.gov/facts
- National Institute of Water and Atmospheric Research (NIWA) New Zealand website: www.niwa.co.nz

- Pirani, R., and Tolkoff, L., (2014). “Lessons from Sandy: Federal policies to build climate-resilient coastal regions. Policy Focus Report”. Cambridge, MA: Lincoln Institute of Land Policy.
- Quarantelli, E.L., (1998). “What is a Disaster?”. Routledge, London.
- Sterman J. D., (2000). “Business dynamics: Systems thinking and modeling for a complex world”. Boston, MA: McGraw-Hill.
- Stirman, S. W., Kimberly, J., Cook, N., Calloway, A., Castro, F., and Charns, M., (2012). “The sustainability of new programs and innovations: a review of the empirical literature and recommendations for future research”. Implementation Science, 7(1), pp 1-19.
- Toro, G. R., (2008). “Joint Probability Analysis of Hurricane Flood Hazards for Mississippi. Final Report”. Risk Engineering, Inc., 70p.
- Toro, G. R., D. T. Resio, D. D., A. W. Niedoroda, and C. Reed, (2010). “Efficient joint-probability methods for hurricane surge frequency analysis”. Ocean Engineering, 37(1), pp 125–34.
- Vickery, P., et al., (2013). “FEMA Region III Storm Surge Study: Coastal Storm Surge Analysis: Storm Forcing”. USACE, ERDC, 156p.
- Warren, K., (2004). “Why has feedback systems thinking struggled to influence strategy and policy formulation? Suggestive evidence, explanations and solutions”. Systems Research and Behavioral Science, 21(4), 331-347
- U.S. Census Bureau 2010: http://www.census.gov/2010census/

- _____. (1999). “Hazard mitigation grant program desk reference”. Washington, DC: Federal Emergency Management Agency, Department of Homeland Security, Mitigation Directorate, Program Support Division, 252p.
- _____. (2006). “Impacts of Climate Variability and Change on Transportation Systems and Infrastructure – Gulf Coast Study”. Climate Change Science Program (CCSP) Synthesis and Assessment Product (SAP) -4.7, 17p.
- _____. (2012). “Joint probability – optimal sampling method for tropical storm surge”. Operating guidance No. 8-12 for use by FEMA staff and flood mapping partners. Washington, DC: Federal Emergency Management Agency, Department of Homeland Security.
- _____. (2014). “Summary report / record of the proceedings”. Centers for Disease Control and Prevention (CDC), Office of Public Health Preparedness and Response (OPHPR), Board Of Scientific Counselors (BSC) Meeting. Atlanta, GA, pp 27-33.
- _____. (2015). “North Atlantic Coast Comprehensive Study: Resilient adaptation to increasing risk – Main report”. Brooklyn, NY: North Atlantic Division, USACE.
- _____. (2015). “North Atlantic Coast Comprehensive Study: Resilient adaptation to increasing risk – Appendix A - Engineering”. Brooklyn, NY: North Atlantic Division, USACE.
- _____. (2015). “North Atlantic Coast Comprehensive Study: Resilient adaptation to increasing risk – Appendix C - Planning Analyses”. Brooklyn, NY: North Atlantic Division, USACE.

Vita

Khatoon Melick was born on December 14, 1978 in Tehran, Iran. In 2001, she received a BSc degree in civil engineering from the K. N. Toosi University of Technology in Tehran, graduating at the top of her class. In February of 2003, she received a MSc degree in civil engineering with a focus in water engineering from Sharif University of Technology in Tehran, graduating second in her class. In 2007, after working several years in Tehran as an engineer and faculty member for various engineering firms and research institutes, the author moved to Baltimore, Maryland to join Professor Robert A. Dalrymple's team as a PhD student in the civil engineering department of Johns Hopkins University. She received a second MSc degree in civil engineering with a focus in coastal engineering from JHU in 2010. In 2011, she started working for Dewberry LLC as a water resources and coastal engineer, moved to Fairfax, Virginia, and took a leave of absence from Johns Hopkins University. In 2015, she joined Professor Takeru Igusa's team to complete her graduate studies. During her studies, she was financially supported by a departmental fellowship, Dewberry, and grants from the National Science Foundation. Khatoon is currently a coastal engineer at Dewberry and a PhD candidate in civil engineering, with a focus in coastal engineering, at Johns Hopkins University.